Phase I Report
Characterization of Lake Livingston and Its Watershed

for
Trinity River Authority

by
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November 2012 (updated July 2013)

Acknowledgements

Funding was provided by the Trinity River Authority for the Phase I – Lake Livingston Watershed Study culminating in this report. Both the study and report were a cooperative effort of Trinity River Authority staff and Texas Institute for Applied Environmental Research staff located at Tarleton State University, Stephenville, TX.

Erratum

Within Chapter 5, Pollutant Loadings to Lake Livingston, the water volumes as presented in Figures 5-1 through 5-4 were misrepresented due to an error in calculating daily volume in cubic feet (ft^3) from average daily flow in cubic feet per second (cfs). In addition, within Figure 5-3 presenting volume normalized based on the watershed area, the watershed area for the Trinity River at Rosser rather than at Crockett had been used. This changed the estimated volume contribution of the Trinity River at Crockett to Lake Livingston from 87 to 80 percent of the total flow.

Because of the miscalculation in the daily volume of streamflow, the back-calculated concentrations from the LOADEST model loading presented in Figures 5-15 through 5-21 were also misrepresented, although the trends discussed in the text and in Table 5-5 remained the same over time and in relation to changes in flow. For Figure 5-21, concentrations of bacteria over time for Bedias Creek are also presented in terms of *E. coli* rather than fecal coliform in this revision.

A corrected Chapter 5 is provided in this July 2013 version of the report.

Executive Summary

Lake Livingston is the largest single-purpose reservoir in Texas, and it is critical to the water supply for the City of Houston, currently the fourth largest municipality in the United States. The construction of Lake Livingston began in the mid-1960s, and the lake was impounded in 1969. The primary purpose of the lake is to provide water supply for the four surrounding counties (Trinity, Polk, San Jacinto and Walker) and municipal, industrial, domestic and irrigational needs for the Houston area. Lake Livingston also provides many recreational uses including fishing, waterskiing, wading and swimming.

Lake Livingston has been assessed by the Texas Commission on Environmental Quality (TCEQ) in recent years as having impairments due to elevated levels of sulfate (SO_4) and high pH readings. In addition, nitrate concentrations approaching the drinking water standard can occur on occasion at the water intake for the City of Huntsville located in the upper portion of the lake. In the absences of individual criterion for nutrients in Texas, TCEQ employs screening levels for ammonia (NH_3), nitrate (NO_3), orthophosphate phosphorus (OP), total phosphorus (TP) and chlorophyll-a (Chl-a) and assigns concerns when these screening levels are assessed as being exceeded. Much of Lake Livingston has been assessed as having concerns for all nutrient-related parameters with screening levels with the exception of NH_3.

Lake Livingston is owned and operated by the Trinity River Authority under contract with the City of Houston and was the focus of the Phase I Characterization Study for the envisioned multi-phased Lake Livingston Watershed Study. In developing this characterization the following objectives were achieved:

- Created a Lake Livingston watershed data inventory
- Selected watershed and lake models
- Analyzed and assessed existing data
- Evaluated water quality monitoring needs
- Developed scope for Phase II study
- Developed Phase I report

The analyses of water quality data focused on the following parameters: NH_3, total Kjeldahl nitrogen (TKN), NO_3, nitrite and nitrate (NO_{23}), OP, TP, Chl-a, SO_4, *Escherichia coli* (*E. coli*), total suspended solids (TSS), five-day biochemical oxygen demand (BOD_5), fecal coliform (Fcoli), pH, alkalinity (Alky) and water temperature (WaterT).

The enormity of the 16,600 square mile watershed of Lake Livingston necessitated restricting the spatial area of the study to that portion of the watershed from the Dallas-Ft. Worth Metroplex (DFW area) to Lake Livingston. The predominately urbanized landscape in the northwest, upstream end of the study area transitions quickly to a rural landscape dominated by pastureland, forest and wetlands. Rainfall patterns in the study area decrease from annual average rainfall amounts of 57 inches in the southeast portion of the watershed to 36 inches in the northwest portion.

From a hydrologic perspective, the dominate source of inflows to Lake Livingston is the Trinity River. Based on analyses in this report an estimated 80 percent of the flow into the lake occurs from the watershed above the Trinity River near Crockett, TX. Important tributaries other than the Trinity River that more locally provide inflow include Bedias Creek, White Rock Creek and Kickapoo Creek. Inflows to Lake Livingston show a strong seasonality with greatest streamflows typically occurring in the winter and spring tapering to a low-flow period of late summer and early fall. The discharges from the large regional wastewater treatment facilities (WWTFs) in the DFW area dominate Trinity River flow under low flow conditions. The steady urban growth in this same area has resulted in increased WWTF discharges over the years, which are reflected in a steady increase in the annual minimum 7-day average flows at U.S. Geological Service (USGS) streamflow gages along the Trinity River.

The DFW area not only influences the hydrology of the study area, but also has importance concerning water quality in the Trinity River down to Lake Livingston. Long-term trend analyses of monitoring data collected 1970 - 2011 along the Trinity River reflect the benefits of efforts from the 1970s through early 1990s that included advanced treatment and more stringent nitrification requirements on WWTFs and what was effectively a nation-wide ban on phosphorus in some types of detergents. Resulting benefits included water quality improvements (i.e., lower in-river concentrations) in the Trinity River for NH_3, TKN, TP, OP and BOD_5. In contrast, NO_3 and NO_{23} have shown an increase, which would be anticipated with imposition of more stringent WWTF requirements that require conversion of organic nitrogen and NH_3 to NO_3. Short-term analyses based on data from 1991-2011 do indicate that more recently the trends for these water quality parameters have reduced to a point of decreased significance. Because of the SO_4 and pH concerns in Lake Livingston, it is notable that the Trinity River data indicate trends of increasing values for both these parameters.

From a spatial perspective, the higher concentrations of nutrient forms in the upper Trinity River show steady decline along the river toward Lake Livingston. The exception is NH_3 which was already at low, near-background levels in the upstream reach and remains at those low levels throughout the river. The decreasing spatial trends in nutrients is most likely being facilitated by the natural assimilative capacity of the Trinity River and dilution from water containing lower concentrations of nutrients below the DFW area. Despite the strongly-decreasing concentrations longitudinally along the river, these various nutrient forms remain near or above TCEQ defined screening levels for rivers even at the most downstream monitoring location on the Trinity River near Crockett, with the exception of NH_3.

Temporal water quality trends are generally not statistically significant at both long-term and short-term scales for streams and creeks that enter the lower Trinity River (Catfish and Tehuacana Creeks) as well as those that flow directly into Lake Livingston (Bedias and Harmon Creeks). Harmon Creek is an exception to this observation with trends for this creek mimicking those for the Trinity River. It is believed this similarity is driven by effluent discharges from the City of Huntsville that enter via a tributary of the creek, thus sharing with the Trinity River influences from urbanization and WWTF discharge. With the exception of Harmon Creek, nutrient forms are below TCEQ screening levels in these creeks.

Estimates of loadings (concentration multiplied by flow) into Lake Livingston for the studied water quality parameters generally indicate the Trinity River as the dominant source; the watershed above the Trinity River near Crockett was estimated to contribute between 75 to 90 percent of loadings for most of the studied parameters. The local inflows for the drainage area to the lake below the Trinity River near Crockett were found to disproportionately contribute loadings of *E. coli*, NH_3 and TKN.

This loading analysis further indicated that nutrient forms such as NO_3 and OP, as well as SO_4, have a strong response of decreasing concentrations with increasing flows on the Trinity River near Crockett, which is an indication of point source contribution of these parameters from the DFW area. In contrast TSS, *E. coli* and TKN show a complex response of increasing concentration on the Trinity River with increasing flow until a flow of approximately 10,000 cubic feet per second (cfs) and then decreasing concentrations. The increasing concentration response of these parameters to flow is a typical nonpoint source signature, and the decreasing concentrations at the highest streamflows are suspected to be a response to releases of relatively good quality water from the numerous large reservoirs in the Trinity River Basin above Lake Livingston under larger runoff events. Analyses of TSS, TKN and fecal coliform on Bedias Creek, used as representing contributions from the lower Lake Livingston watershed, showed a more typical nonpoint-source response of increasing concentrations through the entire range of flows.

Similar to the long-term (1970-2011) and short-term (1991-2011) trend analyses results for the Trinity River, the data at stations in Lake Livingston indicate stronger trends overall for the longer period than for the shorter period. NH_3, TKN, OP and TP decreased in concentration with time. From a spatial perspective, Lake Livingston data for NO_3, NO_{23}, OP, TP and TSS showed notable decreasing downstream concentrations; typically about an order-of-magnitude change. In contrast Chl-a (a direct indicator of phytoplankton or suspended algae) increased from upstream to downstream; at least in part as a response to increased water clarity associated with the downstream decreases in TSS. As a result of the uptake of carbon dioxide during photosynthesis by algae under sunlight (i.e., during the day and peaking in the mid-afternoon), pH concentrations also become higher in the middle and lower portions of the lake. While SO_4 concentrations decrease below the criterion toward the dam, on a lake-wide average they remain at levels at or above the existing SO_4 criterion for Lake Livingston. It should be noted that the effective SO_4 criterion for the lake is 50 mg/L; however, the 2010 Texas Surface Water Quality Standards contain a SO_4 criterion of 60 mg/L. If this higher criterion is approved by the U.S. Environmental Protection Agency, Lake Livingston data will indicate non-impairment for SO_4.

Detailed spatial and temporal analyses of Lake Livingston included evaluating data at a monthly level by monitoring station. This analysis supports a diagnosis that the elevated pH levels in the lake are a response to the photosynthesis activities of phytoplankton as exemplified by the higher pH concentrations prevailing during the growing season of roughly May through September; a pattern shared with Chl-a. Temporal and spatial analyses also indicated that thermal stratification occurs in the deeper waters of the lake near the dam. This stratification is a warm-season response observed where surface waters warm but only mix in the vertical water column to a depth limited by wind-wave turbulence resulting in an isolated cooler and denser bottom layer of water. Data indicate that stratification typically begins in late spring and persists through late summer or early fall. With the onset of cooler weather, the thermal stratification is broken down as the temperature-driven density difference between surface and bottom waters becomes insufficient to prevent wind-wave mixing.

While the understanding of water quality in Lake Livingston, the Trinity River and immediate tributaries has benefitted from a long history of monitoring, certain areas of weakness became apparent through the Phase I study. The following recommendations for the existing monitoring program are being made to overcome these deficits. Additionally, monitoring and subsequent laboratory analyses are resource intensive and always limited by personnel availability and budget constraints. The following recommendations do not consider such constraints, which would drive the decision as to which recommendations to implement.

Recommendations to monitoring program:

- Implement broader routine water quality monitoring in both time and space for the larger creeks directly entering Lake Livingston, such as Kickapoo Creek, White Rock Creek and Bedias Creek, in order to better characterize the importance of local inflows to lake water quality and possible implications on coves and the main body to the lake.
- Increase routine monitoring frequency at key Lake Livingston stations with historical data to better characterize intra-annual water quality.
- Continue a frequent level of monitoring of several times per year at Station 10934 in upper portion of Segment 0805 and Station 13690 in the lower portion of Segment 0804; both on the Trinity River between Lake Livingston and DFW area. Trinity River-located stations such as 10925 and 10922, which have a history of inconsistent monitoring, could be included into this broader monitoring program.
- Within Lake Livingston, implement a seasonally balanced 24-hour DO monitoring program better reflecting TCEQ assessment guidance that indicates at least one half of the 24-hour DO monitoring events must be spaced over an index period representing warm-weather seasons of the year (March 15-October 15), but also considers that although samples over the entire year are not required at this time, current monitoring guidance encourages year-round sampling. Currently a preponderance of 24-hour measurements is concentrated in the months of July – October.

In addition to monitoring, mathematical modeling provides a tool allowing characterization of water bodies and watersheds with the additional benefit that models provide predictive capabilities to evaluate future scenarios and conditions. The Soil & Water Assessment Tool (SWAT) and CE-QUAL-W2 are two proven, nonproprietary models that as a modeling system would provide functionality to simulate the watershed of Lake Livingston and the lake, itself. SWAT is a watershed-scale model used to predict streamflow and water quality parameters as well as the benefits of implementing best management practices and control measures. CE-QUAL-W2 is a two-dimensional model used to predict water quality in lakes and reservoirs by segmenting the water body vertically and longitudinally. When linked, these two models provide a management tool that could be used to evaluate relevant water quality conditions, especially regarding nutrients, dissolved oxygen and total suspended solids in the Lake Livingston watershed and the lake. In application, the large 16,600 square mile Lake Livingston watershed will necessitate a scaling back of the watershed area modeled to that portion in the immediate vicinity of the lake. Streamflow and water quality parameter loadings contributed by the removed portion of the watershed will be included as inputs to the management tool based on gaged streamflow and water quality monitoring data at a key location on the Trinity River.

The findings of the Phase I study provide the basis for Phase II of the project in fiscal year 2013. Recommendations for Phase II include:

- Task 1: Focused review of loading estimates for all water quality parameters developed in Phase I with special attention placed on NO_3 and NO_{23} along the Trinity River and within the upper portion of Lake Livingston to the City of Huntsville water intake at river mile 186.

- Task 2: Initial development of the modeling system focusing on a CE-QUAL-W2 model of Lake Livingston using as a basis the existing Lake Livingston segmentation developed to perform various evaluations of the proposed hydroelectric project on the lake.

    - Expand the existing segmentation of Lake Livingston by extending the present segmentation from its upstream terminus at approximately river mile 172 to at least the end of the lake at river mile 222.
    - Provide the needed inflows and water quality loadings to the model using the loading algorithms developed in Phase I and as enhanced in the first task of Phase II.
    - Provide an initial calibration of the model against measured in-lake data for a selected two-year period within 1993 – 2004; a period of time when extensive monitoring was occurring in Lake Livingston.
    - Operate the model to assess NO_{23} in Lake Livingston focusing on the area of the City of Huntsville water intake. Determine which set of conditions (such as streamflow and seasonality) are most likely to result in heightened concerns of elevated NO_{23} in the upper lake. (Note: As with many water quality models, CE-QUAL-W2 does not separately simulate nitrite and nitrate, but considers them as the lumped parameter of NO_{23}.)

- Task 3: Provide a written report summarizing the evaluation of loadings, extension of the CE-QUAL-W2 model of Lake Livingston, initial calibration of the model, and the results of scenarios accessing NO_{23} in the lake.

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AMLE	Adjusted Maximum Likelihood Estimation
NH_3	Ammonia Nitrogen
AU	Assessment Unit
BMP	Best Management Practice
BASINS	Better Assessment Science Integrating point & Nonpoint Sources
BOD_5	Biochemical Oxygen Demand (5-day)
$CaCO_3$	Calcium Carbonate
CO_2	Carbon Dioxide
Cl^{-1}	Chloride
Chl-a	Chlorophyll-α
CWA	Clean Water Act
cfs	Cubic Feet per Second
DFW	Dallas-Ft. Worth Metroplex
°C	Degrees Centigrade
°F	Degrees Fahrenheit
DO	Dissolved Oxygen
EFDC	Environmental Fluid Dynamics Code
EIH	Environmental Institute of Houston
E. coli	*Escherichia coli*
Fcoli	Fecal Coliform
FORTRAN	Formula Translation/Translator
GIS	Geographic Information System
HSPF	Hydraulic Simulation Program - FORTRAN
km	Kilometer
LOADEST	Load Estimator
MSL	Mean Sea Level
µg/L	Micrograms/liter
mg/L	Milligrams/liter
mL	Milliliter
MGD	Million Gallons per Day
MRLC	Multi-Resolution Land Characteristics Consortium
NCDC	National Climatic Data Center
NLCD	National Land Cover Database
NPDES	National Pollution Discharge Elimination System
NO_3	Nitrate Nitrogen
NO_{23}	Nitrite-Nitrate Nitrogen

nd	No Data
NS	Not Significant
OP	Orthophosphate Phosphorus
PPCC	Probability Plot Correlation Coefficient
SWAT	Soil & Water Assessment Tool
S.U.	Standard Units
SH	State Highway
SO_4	Sulfate
SWQM	Surface Water Quality Monitoring
SWQS	Surface Water Quality Standards
TCEQ	Texas Commission on Environmental Quality
TIAER	Texas Institute for Applied Environmental Research
TPDES	Texas Pollutant Discharge Elimination System
Alky	Total Alkalinity
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TP	Total Phosphorus
TSS	Total Suspended Solids
TRA	Trinity River Authority
USEPA	U.S. Environmental Protection Agency
USGS	United States Geological Survey
WWTF	Wastewater Treatment Facility
WASP	Water Quality Analysis Simulation Program
WaterT	Water Temperature

Chapter 1
Introduction

General Description of Lake Livingston

Lake Livingston is the largest single-purpose reservoir in Texas, and it is critical to the water supply for the City of Houston, currently the fourth largest municipality in the United States. The construction of Lake Livingston began in the mid-1960s, and the lake was impounded in 1969. The normal pool level is 131 ft MSL and the storage capacity is 1.75 million acre-feet. The surface area is about 90,000 acres. The reservoir is generally shallow, with most of its area at depths of 30 ft or less, though near the dam and in the old river channel depths are predominately greater than 30 ft, with maximum depths of about 90 ft. The main body is approximately 30 miles in length with a shoreline of more than 450 miles. The primary purpose of Lake Livingston is to provide water supply for the four surrounding counties (Trinity, Polk, San Jacinto and Walker) and municipal, industrial, domestic and irrigational needs for the Houston area. Lake Livingston also provides many recreational uses including fishing, waterskiing, wading and swimming.

Agencies, such as the United States Geological Survey (USGS) and Trinity River Authority (TRA), have collected water quality data on Lake Livingston since its initial impoundment (TRA 1976; Espey & Padden 1998). Although inflow to Lake Livingston is mainly derived from the Trinity River, tributaries including Harmon Creek, White Rock Creek, Kickapoo Creek and Bedias Creek are important water sources during storm runoff. Through monitoring of Lake Livingston, a variety of water quality problems have emerged as noted in various sources (Table 1-1) and through assessments by Texas Commission on Environmental Quality (TCEQ).

Within the State of Texas, the TCEQ has responsibility for assessing waters for concerns and impairments. According to the TCEQ's Surface Water Quality Standards (SWQS), streams and water bodies in Texas are subdivided into classified segments, which "have relatively homogeneous chemical, physical, and hydrological characteristics" (TCEQ, 2010a). Each individual segment "provides a basic unit for assigning site-specific standards and for applying water quality management programs of the agency." Lake Livingston is designated as Segment 0803 (Lake Livingston), and the upstream adjacent segment is 0804 (Trinity River above Lake Livingston). Each segment is further subdivided into assessment units (AUs), which are the smallest geographic areas employed by TCEQ for assessment purposes (TCEQ, 2010b).

Table 1-1 History of water quality problems in Lake Livingston.

Study Period	Water Quality Problems/Concerns	References
1969-1992	Possible increases in chlordane and dieldrin	Van Metre and Callender 1996
1971-1991	Significant sink for nutrients traveling down the Trinity River	Van Metre, P.C. and D. C. Reutter 1995
1972-1975	Substantial eutrophication problem; problem parameters including fecal and total coliform, chromium, lead, manganese, mercury, ammonia, color, and suspended solids; thermal stratification in the main body; poor water quality in the upper reaches	TRA 1976
1976-1977	Eutrophication concern	McCullough et al. 1977
1982-1992	Parameters of concern include total phosphorus; possible concerns include sulfate, nitrate nitrogen, total Kjeldahl nitrogen, and dissolved orthophosphate phosphorus	APAI 1994
1982-1992	Contaminant load from upstream segment; dissolved oxygen level below standards; nutrient levels periodically exceed screening criteria	APAI 1996
1987-1992	Low dissolved oxygen levels in the upper reach; localized excessive phytoplankton growths; high organic and nutrient loading to the lake by the mainstem of Trinity River	APAI 1992
1988-1997	Depressed dissolved oxygen in north end; elevated fecal coliform level at upper end, Bedias, Nelson and White Rock Creeks; numerous exceedances of surface screening levels for both nitrite+nitrate and total phosphorus and orthophosphate phosphorus at upper lake	Espey & Padden 1998
1987-1998	Several minor exceedances of the primary drinking water standard for nitrates; numerous nitrate values greater than the screening level in upper stations of the lake; numerous nitrate+nitrite values throughout greater than the screening level; numerous total phosphorus and orthophosphate phosphorus greater than applicable screening levels.	Espey & Padden 1999

As required under Sections 305(b) and 303 (d) of the federal Clean Water Act (CWA), biennially TCEQ assesses the waters of the State of Texas and develops the "303(d)" list that identifies the water bodies in or bordering Texas not meeting applicable surface water quality standards, which are set to protect the uses designated for those water bodies. Lake Livingston has been on the Texas 303(d) list since 2008 for high pH in AUs 0803_01 and 0803_06 and since 2006 for SO_4 in all AUs in Segment 0803 (Table 1-2). In June 2010, TCEQ adopted numerical nutrient criteria for 75 reservoirs in terms of concentrations of chlorophyll-a. For Lake Livingston, the chlorophyll-a criterion is 22.96 µg/L compared to the long-term average at station 10899, which is located in the main body of the reservoir near the dam. This criterion, as well as numeric nutrient criteria associated with other Texas lakes and reservoirs, is still pending U.S. Environmental Protection Agency (USEPA) approval as of October 2012. Historically, in addition to pH, Lake Livingston has been listed as impaired for depressed DO, SO_4 and bacteria, mostly assessed as fecal coliform prior to 2002 and as *E. coli* after 2002 (Table 1-2).

Because of these water quality impairments and concerns, the TRA is preparing to address future management needs for Lake Livingston and its watershed.

Table 1-2 Historical 303(d) listings for Segments 0803 & 0804 including Lake Livingston and several tributaries.

Year of 303 (d) List	Segment Number/Name	Water Quality Parameter Problems/Concerns
1992	0804/Trinity River Above Lake Livingston	High point sources: large size, high use; low DO, eutrophication, fecal coliform
1996	0804/Trinity River Above Lake Livingston	Depressed dissolved oxygen concentrations; elevated fecal coliform bacteria levels
1998	0803/Lake Livingston	DO concentrations sometimes lower than standard; measured pH values sometimes higher than segment criterion
1998	0804/Trinity River Above Lake Livingston	Mean dissolved cadmium and lead concentrations exceed criteria; bacteria levels sometimes exceed criterion
1999	0803/Lake Livingston	DO concentrations sometimes lower than the standard; measured pH values sometimes higher than criterion
1999	0804/Trinity River Above Lake Livingston	Mean dissolved lead concentrations exceed criterion; bacteria levels sometimes exceed criterion.
2000	0803/Lake Livingston	Depressed DO, high pH
2000	0804/Trinity River Above Lake Livingston	Bacteria
2002	0803/Lake Livingston	Depressed DO, high pH
2004	0803/Lake Livingston	Depressed DO, high pH
2006	0803/Lake Livingston	Depressed DO, sulfate
2006	0804G/Catfish Creek	Depressed DO; impaired macrobenthic community
2008	0803/Lake Livingston	pH; sulfate
2008	0804G/Catfish Creek	Depressed DO; impaired macrobenthic community
2010	0803/Lake Livingston	pH; sulfate
2010	0803G/Lake Madisonville	Mercury in edible tissue
2010	0804/Trinity River Above Lake Livingston	Dioxin in edible tissue; PCBs in edible tissue
2010	0804G/Catfish Creek	Bacteria; depressed DO
2010	0804H/Upper Keechi Creek	Depressed DO

Objectives of Phase I Study

The Trinity River Authority (TRA) with assistance from the Texas Institute for Applied Environmental Research (TIAER) at Tarleton State University conducted a characterization study of Lake Livingston and its more immediate watershed. For this Phase 1 study the major goal was to characterize Lake Livingston and its watershed. To accomplish this goal the following objectives were achieved:

1. Created a Lake Livingston watershed data inventory
2. Selected watershed and lake models
3. Analyzed and assessed existing data
4. Evaluated water quality monitoring needs
5. Developed scope for Phase II study
6. Developed Phase I report

As the deliverable under Objective 6, this report provides information on Objectives 1 – 4. Objective 5 is only addressed in this report as recommendations for the Phase II study. The data inventory created for Lake Livingston under Objective 1 includes the following:

- Relevant GIS data
- Flow and reservoir elevation/storage data
- Water quality-related data
- Permit and location information on regulated sources
- Existing fish survey data
- Weather data around the lake (not addressed extensively in this report)

The analyses and assessments included in this report are to:

- Analyze trends on historical water quality data,
- Correlate watershed and reservoir conditions to water quality,
- Estimate loadings from Trinity River,
- Estimate loadings from direct tributaries to reservoir,
- Identify broad categories of sources and causes of loadings, and
- Identify any potential threats to Lake Livingston.

Chapter 2
Background of Lake Livingston Watershed

Watershed Characteristics

The drainage area of the entire Trinity River watershed is about 18,000 square miles and extends over 350 miles from south of Oklahoma border in North Central Texas to Galveston Bay in southeast Texas. The drainage area contains the entire Dallas-Fort Worth metropolitan area with a population of over six million. The watershed above Lake Livingston comprises approximately 16,600 square miles with its headwaters in North Central Texas and its downstream terminus near the town of Livingston in Southeast Texas (Bureau of Reclamation 1993). Based on geomorphology and bathymetry, Lake Livingston may be divided into three sections: upper riverine (from upper limits of headwaters to the Riverside station), transition from riverine to reservoir (from Riverside station to US 190) and main body (from US 190 to the dam).

The study area covered in this report includes Segments 0803 (Lake Livingston), 0804 (Trinity River above Lake Livingston) and 0805 (Upper Trinity River), extending northwest from the Lake Livingston Dam up into the DFW area (Figure 2-1). Lake Livingston's principal tributaries are from southwest to east Harmon Creek (Segment 803A), Nelson Creek (0803E), Bedias Creek (0803F), Trinity River (0804 & 0805), White Rock Creek (0803B) and Kickapoo Creek (no segment identification; Figure 2-2). Lake Livingston is situated in the South Central Plains of Texas (Level III Ecoregion 35; Griffin et al., 2007), a region characterized by piney woods and acidic sandy-loam soil that is largely forested, especially to the east. The watershed draining into Lake Livingston begins in the rich, clayey soils of the Texas Blackland Prairie (Ecoregion 32) around the DFW area and extends through the East Central Texas Plains (i.e., Post Oak Savanna; Ecoregion 33) dominated by range and pasture land.

Designated Uses for Lake Livingston

The Texas Surface Water Quality Standards assign to Lake Livingston the uses of primary contact recreation, high aquatic life, domestic water supply and general, which are protected by the criteria and screening levels listed in Table 2-1 (TCEQ, 2010a). These criteria/screening levels are applicable to the mixed surface layer in a water column profile, which is defined as the portion of the water column from the surface to the depth at which water temperature decreases more than 0.5 degrees Celsius. Dissolved oxygen (mean of measurements) and pH (median of measurements) criteria apply to the entire mixed water column when a profile of measurements is reported and the water column is not stratified, or only to measurements made in the mixed surface layer if the water column is stratified.

For purposes of analyses presented in this report, near-surface measurements and water samples were considered representative of the mixed surface layer in Lake Livingston.

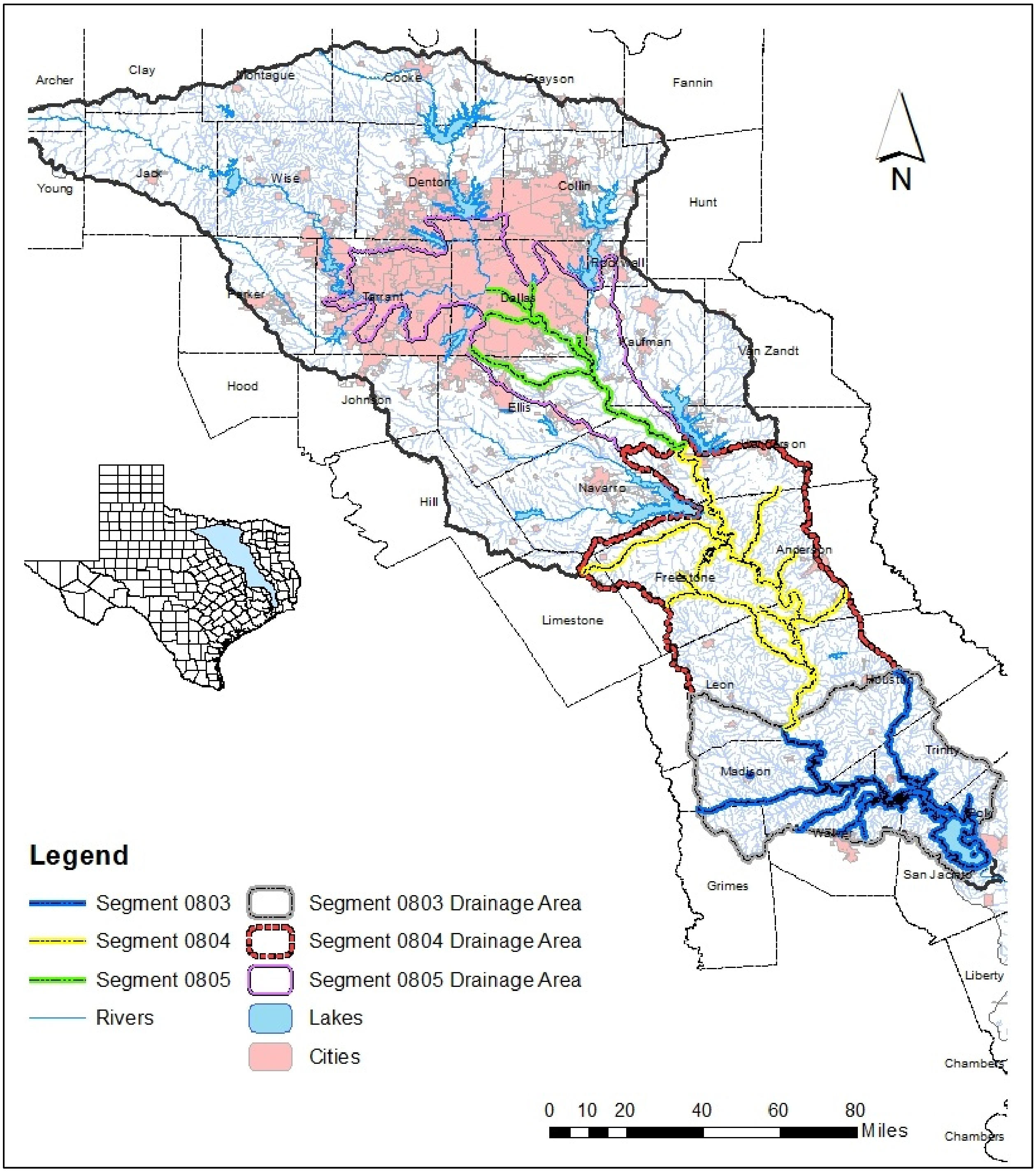

Figure 2-1 Lake Livingston watershed showing Segments 0803, 0804 and 0805.

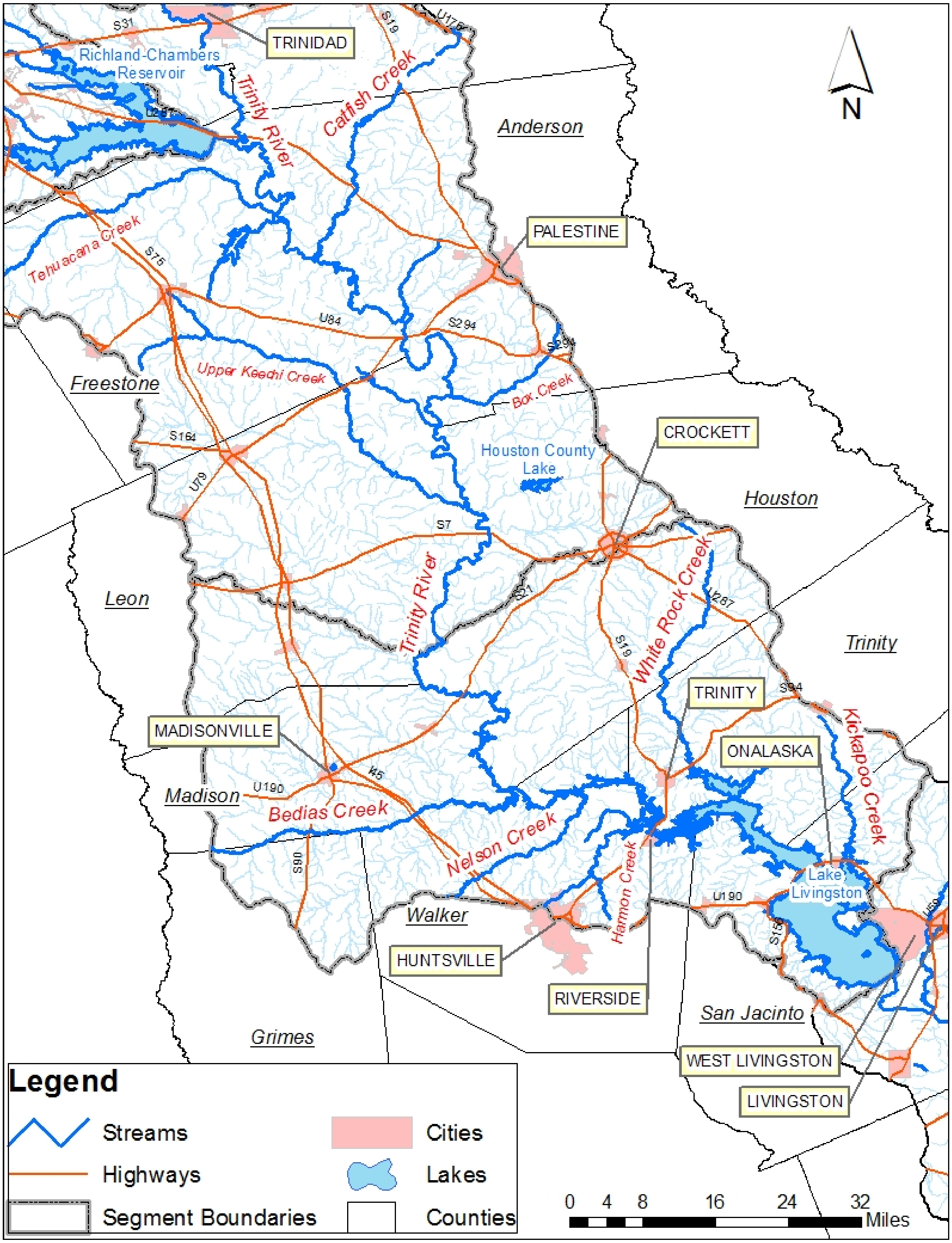

Figure 2-2 Trinity River (Segment 0804) and Lake Livingston (Segment 0803) and principal tributaries.

Table 2-1 Water quality criteria and screening levels for Lake Livingston.

Designated Use	Criteria/Screening Level	Value or Range
High Aquatic Life	24-hr. Average Dissolved Oxygen	5 mg/L
High Aquatic Life	24-hr. Minimum Dissolved Oxygen	3 mg/L
Primary Contact Recreation	*E. coli* (geometric mean)	126 colonies/100 mL
Primary Contact Recreation	Fecal Coliform (geometric mean) [1]	200 colonies/100 mL
General	Chloride [2]	150 mg/L
General	Sulfate [2]	50 mg/L [4]
General	Total Dissolved Solids [2]	500 mg/L
General	pH	6.5 – 9.0 S.U.
General	Water Temperature	93 ºF (33.9 ºC)
General	Nitrate	0.37 mg/L
General	Orthophosphate Phosphorus	0.05 mg/L
General	Ammonia Nitrogen	0.11 mg/L
General	Total Phosphorus	0.20 mg/L
General	Chlorophyll-a	26.70 µg/L
Site-Specific Nutrient Criteria	Chlorophyll-a [3]	22.96 µg/L

[1] *E. coli* replaced fecal coliform as the preferred indicator bacteria in the 2000 Texas Surface Water Quality Standards.

[2] Criterion is based on maximum annual average for the segment.

[3] Site-specific nutrient criteria listed in 2010 Texas Surface Water Quality Standards; based on long-term median values for TCEQ Station 10899; not approved by U.S. Environmental Protection Agency as of October 2012.

[4] The present applicable sulfate criterion is 50 mg/L; the 2010 Texas Surface Water Quality Standards has the criterion increased to 60 mg/L and this higher value is not approved by USEPA as of October 2012.

Summary of Weather Conditions

Average summer temperatures at Lake Livingston peak in July and August around 84 °F and the coldest months are December and January with average daily temperatures around 50 °F (Figure 2-3; NCDC, 2012). Seasonal temperatures are slightly more variable in the upper watershed with daily average temperatures in July and August for Dallas around 86 °F and in December and January about 47 °F. Precipitation near Lake Livingston is bimodal with peaks in May – June and October – December. Rainfall in May – June accounts for about 20 percent of the total annual average precipitation of 52 inches at the lake. Average precipitation gradually decreases moving upstream in the watershed from an annual average of 57 inches southeast of the Lake Livingston to 45 inches at Crockett, Texas near the middle of the study area to 36 inches at the Dallas Fort Worth International Airport at the northwest extremity of the study area (NCDC data accessed 2012). Storms are more common in the spring and fall and the lake is occasionally impacted by hurricanes. Hurricane Rita did significant damage to the dam in September 2005, and the lake was hit three years later by Hurricane Ike in September 2008.

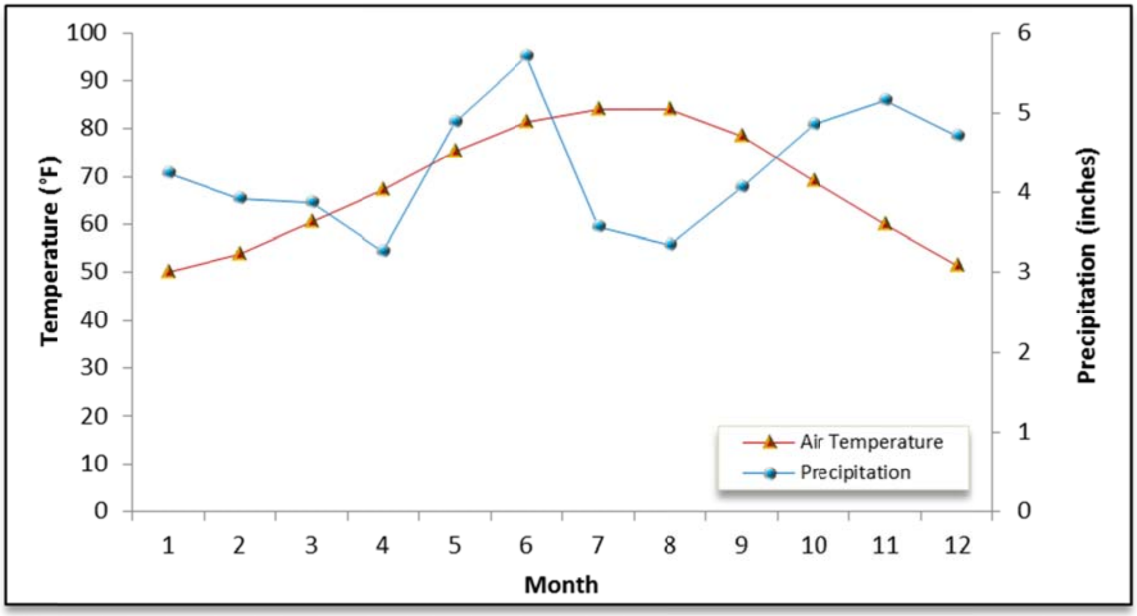

Figure 2-3 Monthly average air temperatures and precipitation (1981-2010) at Lake Livingston (USC00415271). Source: NCDC, 2012.

Land Use and Land Cover

Based on 2006 land use data, pasture/hay dominates Segments 0804 (35%) and 0803 (34%; Figure 2-4 and Table 2-2). The aggregate of open, low-intensity, medium-intensity and high-intensity developed land accounts for 42 percent of land use in Segment 0805 but diminishes to 7 percent in 0804 and 6 percent in Segment 0803. Wetlands are very minor in the upper watershed but account for approximately 14 percent of Segments 0804 and 0803. Wetlands and forest combined account for nearly 40 percent of the two lower segments. In summary, the predominately developed urban land uses of the upper watershed give way to agriculture in Segment 0804. Forest, wetlands, pasture and native grassland become dominant in Segment 0803, particularly in the lower half of the segment. These land use/land cover data are a product of the cooperative mapping effort of the Multi-Resolution Land Characteristics Consortium (MRLC), and the presented geographic information layer (GIS) is commonly referred to as the National Land Cover Database 2006 (NLCD2006; Fry et al., 2011).

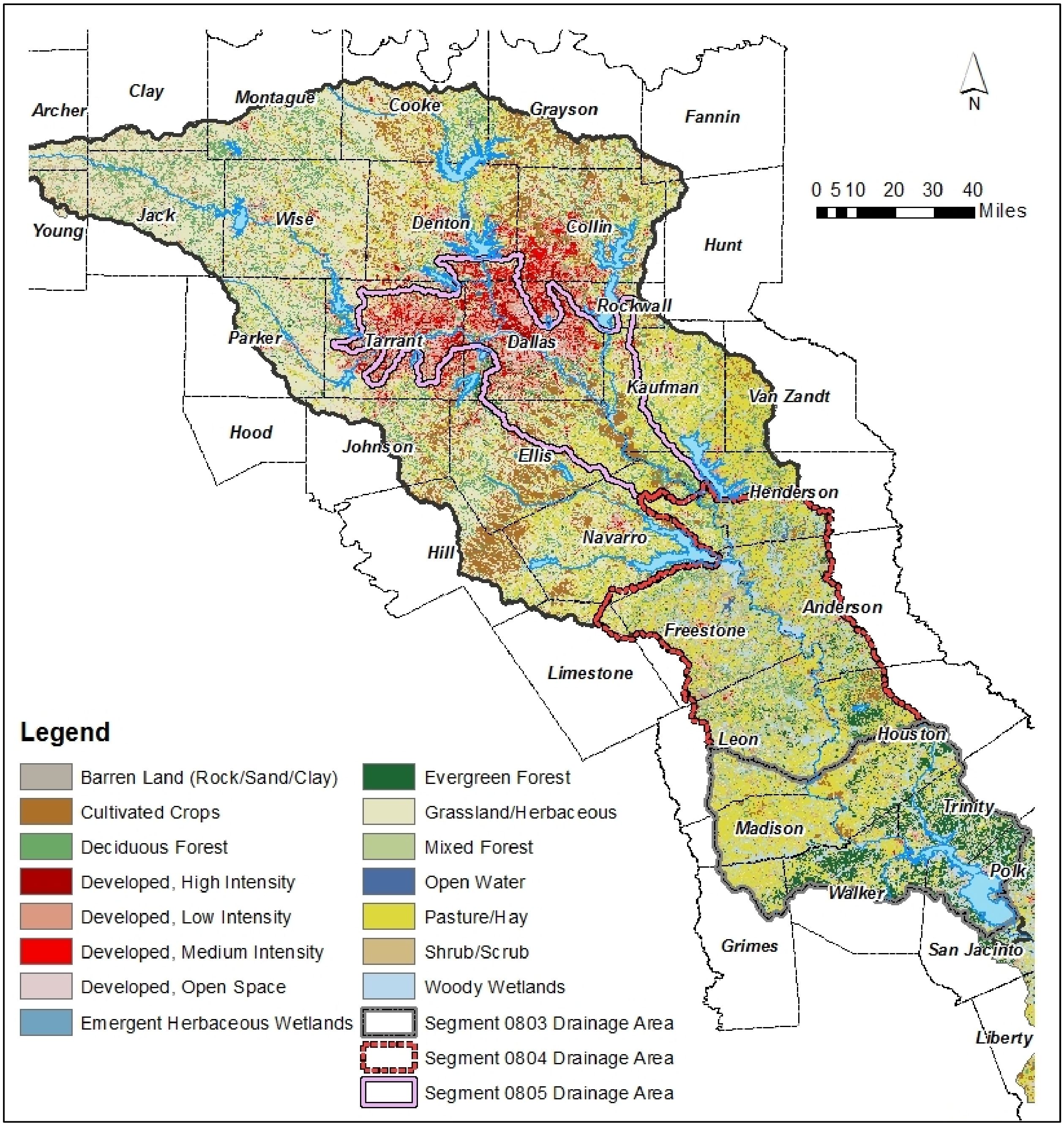

Figure 2-4 Land use and land cover for the Lake Livingston watershed, Segments 0803, 0804 and 0805 (Fry et al., 2011).

Table 2-2 Land use in the Lake Livingston watershed, Segments 0805, 0804 and 0803 (Source: Fry et al., 2011). Land use categories are sorted by total acres represented within all three segments.

SEGMENT	0805		0804		0803		TOTAL	
LAND USE CATEGORY	Area (acres)	Percent (%)	Area (acres)	Percent (%)	Area (acres)	Percent (%)	Area (acres)	Percent (%)
Pasture/Hay	200,592	15.05	618,968	34.90	500,526	33.54	1,290,292	28.54
Woody Wetlands	30,454	2.28	240,787	13.58	195,069	13.07	463,040	10.24
Grassland/Herbaceous	251,698	18.88	103,607	5.84	89,198	5.98	429,427	9.50
Evergreen Forest	9,552	0.72	74,606	4.21	279,000	18.70	362,105	8.01
Deciduous Forest	137,164	10.29	185,171	10.44	13,508	0.91	323,149	7.15
Developed, Low Intensity	210,801	15.82	51,967	2.93	35,711	2.39	297,416	6.58
Shrub/Scrub	4,130	0.31	168,621	9.51	111,010	7.44	280,646	6.21
Developed, Open Space	147,912	11.10	60,649	3.42	50,606	3.39	256,144	5.67
Mixed Forest	171	0.01	155,560	8.77	95,946	6.43	251,608	5.57
Cultivated Crops	106,957	8.02	52,749	2.97	24,978	1.67	178,373	3.95
Developed, Medium Intensity	122,610	9.20	5,835	0.33	2,690	0.18	130,953	2.90
Open Water	21,193	1.59	26,366	1.49	85,059	5.70	130,761	2.89
Developed, High Intensity	78,322	5.88	1,981	0.11	724	0.05	80,978	1.79
Barren Land (Rock/Sand/Clay)	2,619	0.20	20,737	1.17	1,828	0.12	25,117	0.56
Emergent Herbaceous Wetlands	8,673	0.65	6,040	0.34	6,423	0.43	20,830	0.46
TOTAL	**1,332,848**		**1,695,715**		**1,492,276**		**4,520,839**	

Hydrology

Trinity River

Water quality in the Trinity River is affected by effluents from several large WWTFs and storm water runoff from urbanized areas. The climate of the Trinity River watershed is largely subtropical humid, and the watershed is dependent on precipitation for natural streamflow. During dry weather, however, flow of the Trinity River is dominated by WWTF effluents, which are primarily return flows. As early as 1900, the water quality of Trinity River downstream from the Dallas-Fort Worth was impacted by a growing metropolitan area. From 1910-1920 sewage collection and treatment improved, but water quality remained poor until the early 1970s. Since 1972, regional WWTFs have been built within the DFW area to eliminate many community-owned WWTFs, which afforded only primary wastewater treatment. Water quality has continued to improve since this consolidation because of efforts by regional WWTFs to upgrade, expand and use more advanced wastewater treatments (TRA, 1996). Minimum flow levels in the Trinity River continue to increase with the growing population within the watershed. Three USGS stations along the Trinity River mainstem were selected to demonstrate the increasing trend of the annual minimum 7-day average flows from 1970 to 2011 (Figures 2-5 and 2-6).

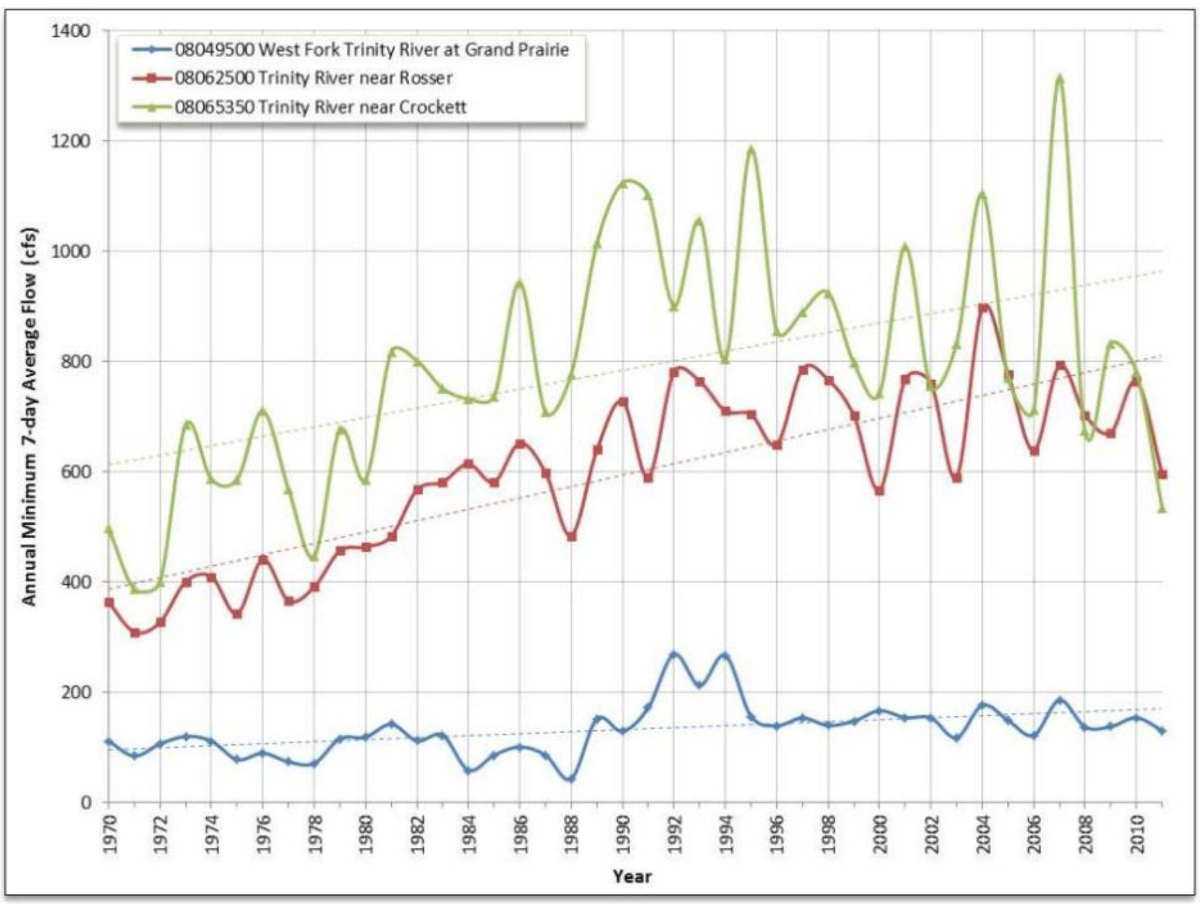

Figure 2-5 Annual minimum 7-day average flows during 1970-2011 for USGS Stations 08049500 (West Fork Trinity River), 08062500 (Trinity River near Rosser) and 08065350 (Trinity River near Crockett).

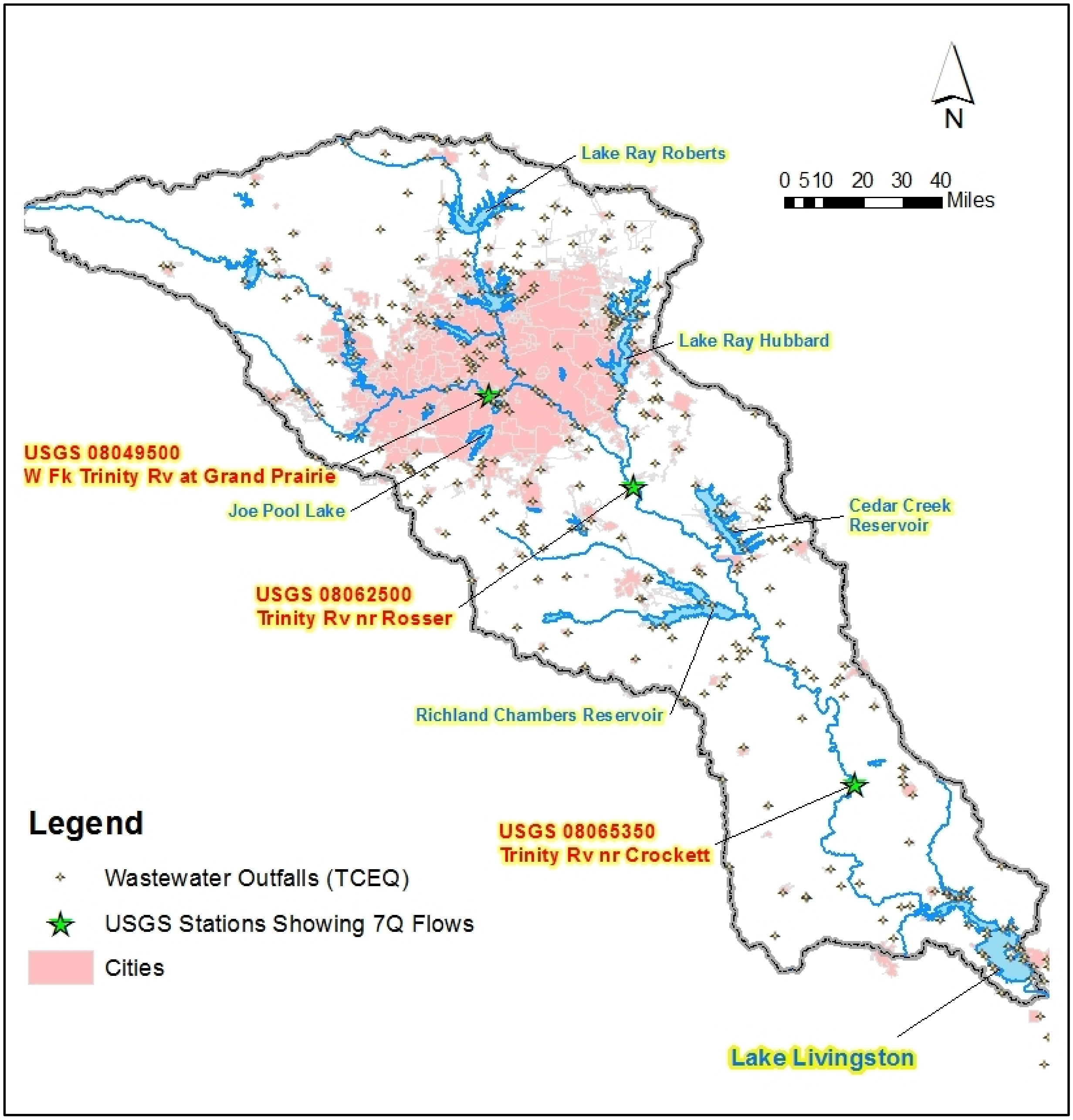

Figure 2-6 Lake Livingston watershed with WWTF outfalls and USGS stations 08049500 (West Fork Trinity River at Grand Prairie), 08062500 (Trinity River near Rosser) and 08065350 (Trinity River near Crockett).

Lake Livingston

USGS gage 08065350 near Crockett, Texas, is the nearest gage above Lake Livingston, and it provides a complete record of daily average discharge from 1970 to the present. Overall, streamflow in the past 40 years has seen a slight uptick (Figure 2-7A), but during the recent 20 years, inflows from the Trinity River to the upper reaches of Lake Livingston have decreased slightly (Figure 2-7B). Discharges from the DFW WWTFs have increased steadily over the past 20 years yet the amount of flow along the Trinity River at Crockett, Texas, has declined. A breakpoint is apparent in 1996, a year when high flow events were rare, relative to the previous six years. This alone does not explain the downward trend since a small decline is still present when trend analysis is restricted to 1991 – 2010. Likely explanations for the recent downward trend in flow are threefold: 1) long-term cyclic variations in temperature and precipitation, 2) increased water demand from the DFW area and 3) hydrologic influences of reservoirs built in the watershed during the late 1970s and 1980s – Lake Ray Hubbard (1978), Joe Pool Lake (1986), Ray Roberts Lake (1986), and Richland Chambers Reservoir (1987) (Figure 2-6). Similar to flows along the Trinity River at Crockett (Figure 2-7B), releases from Lake Livingston Dam from 1991-2010 showed a similar, gradual decreasing trend (Figure 2-8).

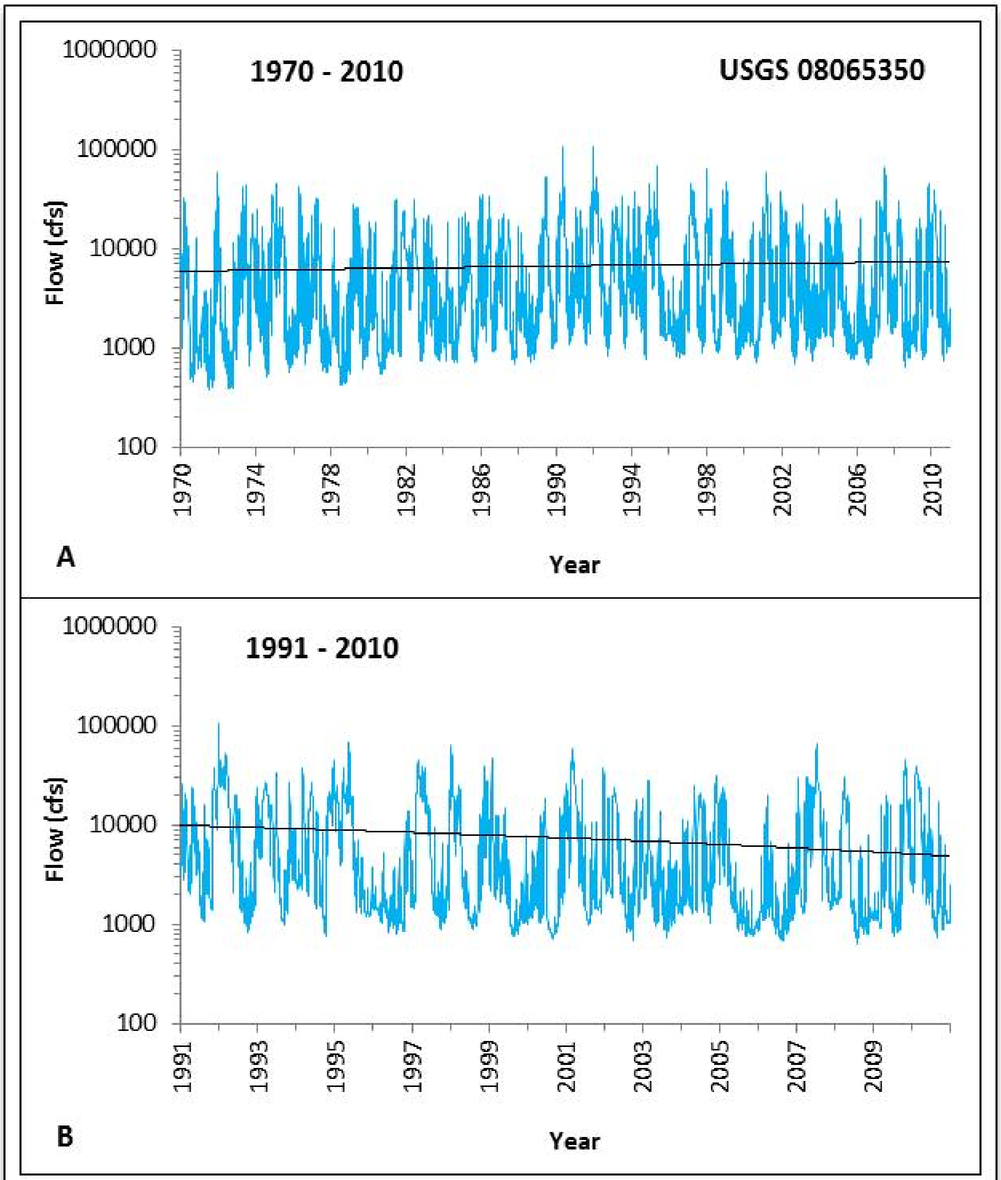

Figure 2-7 Trinity River daily streamflows at USGS 08065350 near Crockett, Texas for 1970 – 2010 (A) and 1991 – 2010 (B).

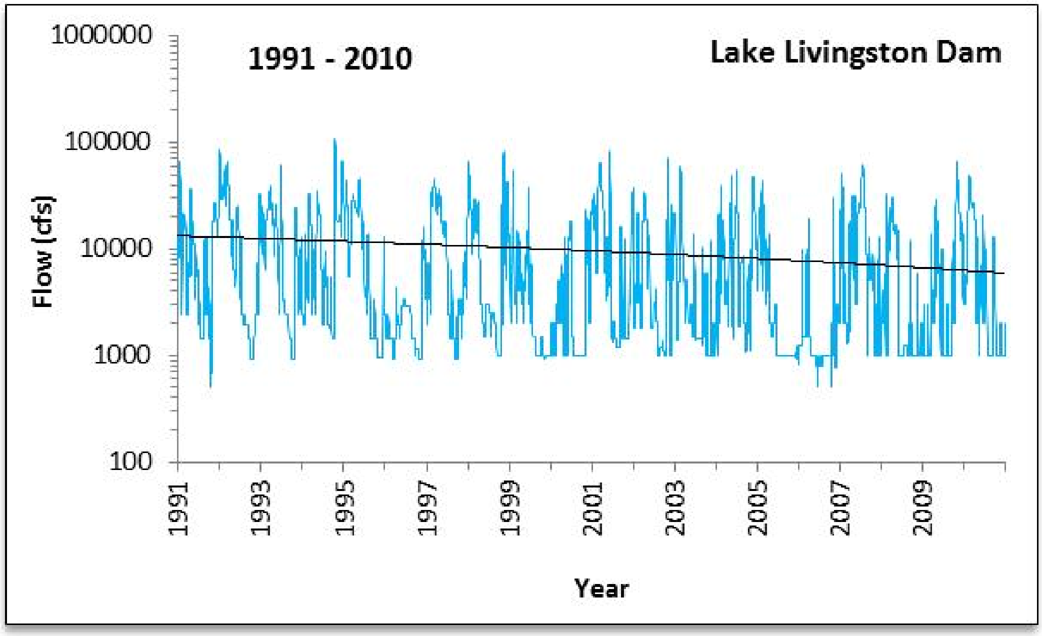

Figure 2-8 Releases at Lake Livingston Dam, 1991 – 2010.

Inflows to Lake Livingston demonstrate distinct seasonality as flows are considerably lower during the late summer months of July – September and higher in the winter and spring (Figure 2-9).

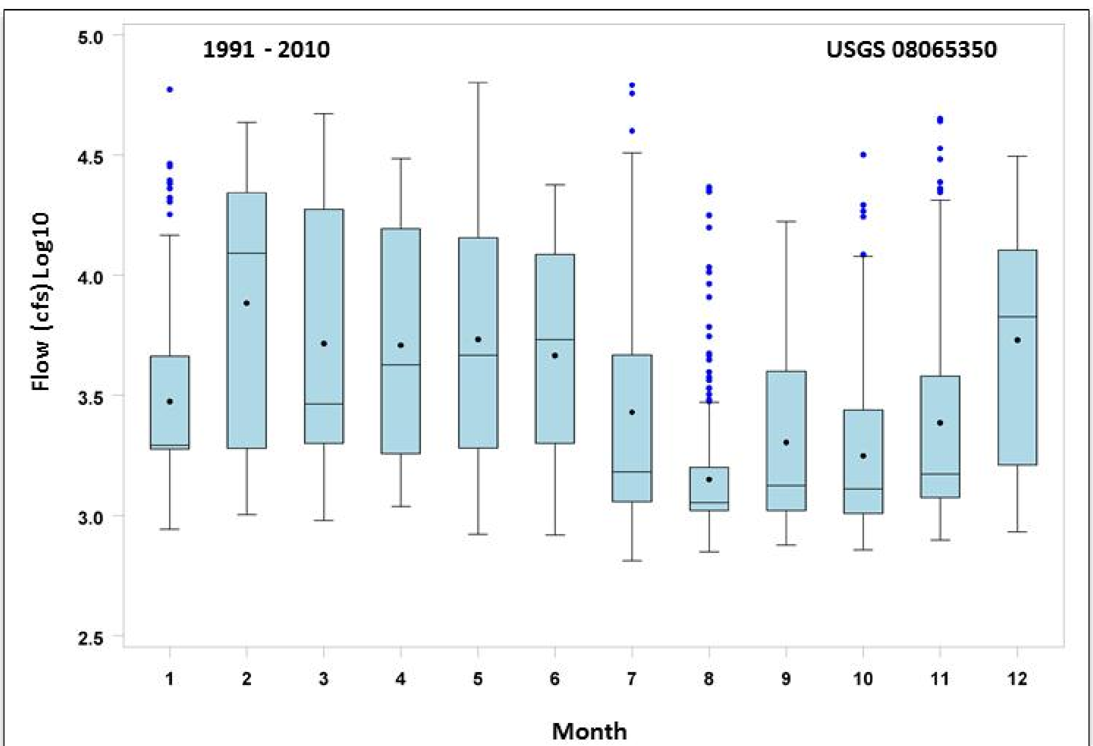

Figure 2-9 Trinity River daily average flows by month at USGS 08065350 near Crockett, Texas, 1991 – 2010.

The average annual retention of Lake Livingston, based on conservation pool storage and annual-average lake releases from 1991 – 2010, is 0.98 years (Figure 2-10). Thus, on average water entering the lake will reside there about 1 year, though in a wet year this retention time drops to as low as 0.5 years and during a dry year increases to 2.0 years. After a high release period in the 1990s (i.e., annual retention times less than the average), the remaining years of the 20-year period showed short alternating periods of above and below average retention times until the consistently dry period of 2008-2010. Although data from 2011 were not included, it is anticipated that the drought of 2011 would continue this sequence of dryer than average years.

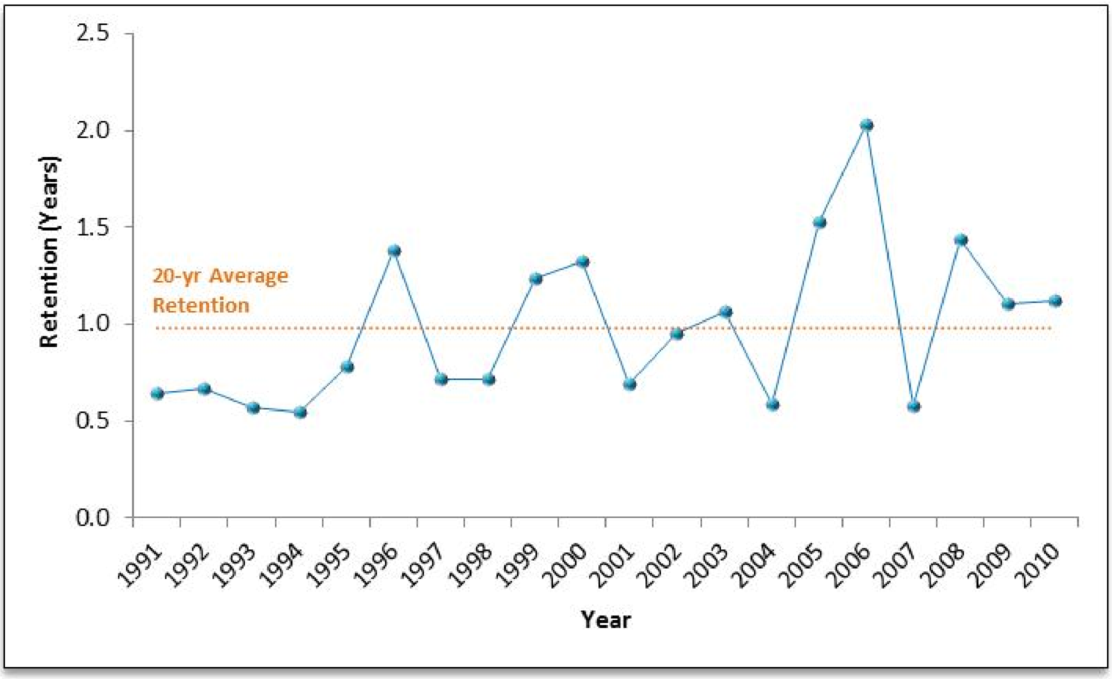

Figure 2-10 Twenty-year trend in annual average retention for Lake Livingston based on dam releases and flow at USGS 08065350 near Crockett, Texas.

Stratification Patterns in Lake Livingston

Thermal stratification is a common summer occurrence in lakes and reservoirs where depth combines with weak hydraulic forces and the depth limitations of wind mixing to create a mixed, heated surface layer (epilimnion) overlying cool benthic water (hypolimnion; August 1993 in Figure 2-11). The metalimnion or thermocline develops as a transition zone where temperatures rapidly decrease with depth. Because the density of water is less at higher temperatures, the vertical temperature pattern also results in a density stratification of the water column with warmer, less dense water on top and cooler, denser water on the bottom, enhancing the stability of this vertical pattern. As thermal stratification persists over a period of weeks to months, vertical gradients typically form for chemical constituents and physical parameters in addition to temperature, so that the limnological distinctions between the epilimnion and hypolimnion become increasingly stark. Biochemical processes and sediment-water interactions in the hypolimnion create anoxic conditions that lower pH and lead to higher concentrations of nutrients and ions through releases from the sediment, which are trapped by the vertical density gradients of the water column and prevented from mixing with the warmer less dense epilimnion. In most Texas lakes stratification is relatively short lived, usually a few months in the deepest reservoirs. High winds, storms and cooler air temperatures with the onset of late summer and early fall eventually destabilize density gradients, and mixing of the entire water column occurs resulting in uniform readings for most water quality parameters regardless of depth (see February 1993 in Figure 2-11).

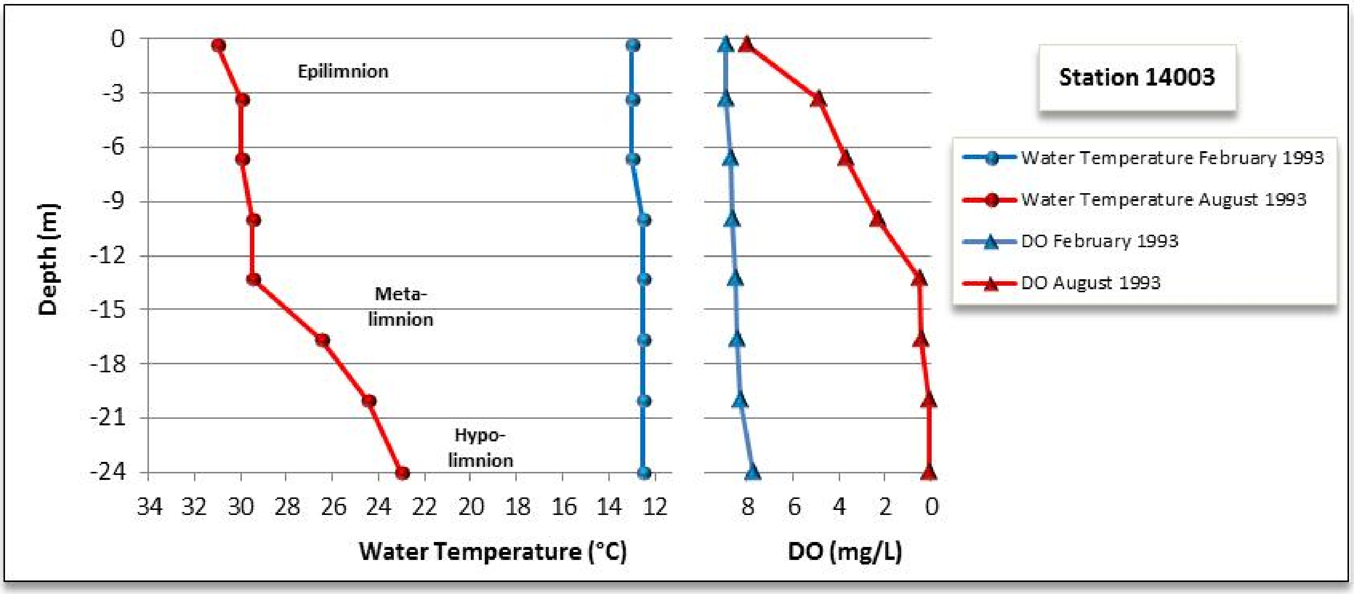

Figure 2-11 Examples of thermal stratification (25 August 1993) and equilibrium (24 February 1993) at Station 14003 immediately above the dam.

In Lake Livingston stratification is typically a summer condition when surface water temperatures peak and the absolute difference between surface and bottom temperatures is greatest (Figure 2-12). Profile data exists for stations near the dam for almost every year between 1970 – 1998 and a few years between 1999 – 2010. According to these data, stratification has been a predictable summer state of these sampling locations. Even when thermal stratification was relatively weak, DO, ammonia and other nutrients had strongly divergent concentrations between the surface and bottom samples during the warm season. Spatially, stratification is most strong nearer the dam due to prevailing depths greater than 30 ft in this area and the resistance of deeper layers to the effects of wind mixing. As evidence, seasonally larger differences between surface and bottom water temperatures occur for a station near the dam compared to a mid-lake station (Figure 2-12).

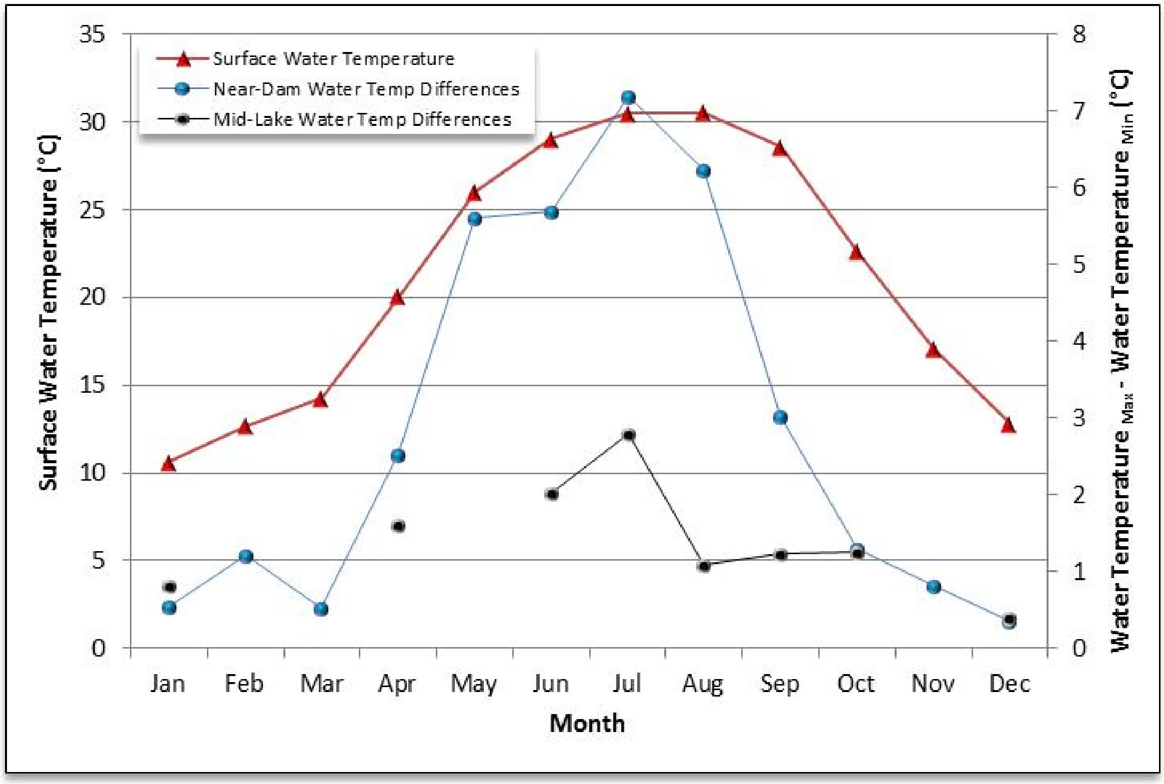

Figure 2-12 Average monthly surface water temperatures (left axis) and differences between maximum and minimum temperatures (right axis) in profile datasets at a near-dam and mid-lake station, years 1974 – 2010.

WWTF Discharges in the Immediate Lake Livingston Area

Pollution sources that are regulated have permits under the Texas Pollutant Discharge Elimination System (TPDES) and the National Pollution Discharge Elimination System (NPDES). Within this report the discussion is limited to WWTF discharges. There are nearly three dozen TPDES/NPDES permitted dischargers in the local Lake Livingston watershed (Segment 0803). The largest permits belong to the City of Huntsville (4.14 million gallons per day (MGD)) and the Texas Department of Corrections (1.15 MGD), both in Walker County (Figure 2-13 and Table 2-3). The largest dischargers on the shores of Lake Livingston are Polk County FWSD 2 (0.26 MGD) and Memorial Point UD (0.2 MGD). All other permits near the lake shore are under 0.2 MGD.

Table 2-3 Permitted dischargers in Segment 0803 in order of permitted discharge.

TPDES Permit	NPDES Permit	County	Map #	Permittee	Full Permitted Discharge (MGD)
10781-003	72974	WALKER	1	CITY OF HUNTSVILLE	4.15
11180-002	92789	WALKER	2	TEXAS DEPT OF CRIMINAL JUSTICE	1.5
11181-001	31593	HOUSTON	3	TEXAS DEPT OF CRIMINAL JUSTICE	0.98
11176-001	31615	MADISON	4	TEXAS DEPT OF CRIMINAL JUSTICE	0.975
10215-001	26662	MADISON	5	CITY OF MADISONVILLE	0.94
11180-001	31607	WALKER	6	TEXAS DEPT OF CRIMINAL JUSTICE	0.85
10617-001	88811	TRINITY	7	CITY OF TRINITY	0.61
10154-002	25895	HOUSTON	8	CITY OF CROCKETT	0.5
11298-001	78841	POLK	9	POLK COUNTY FWSD 2	0.26
10556-001	76104	TRINITY	10	CITY OF GROVETON	0.22
11147-001	22845	POLK	11	MEMORIAL POINT UD	0.2
11300-001	27677	TRINITY	12	WESTWOOD SHORES MUD	0.2
10997-001	21083	SAN JACINTO	13	CAPE ROYALE UD	0.15
01896-000	63401	MADISON	14	MONTEREY MUSHROOMS INC	0.121
10734-001	27138	HOUSTON	15	CITY OF LOVELADY	0.105
11447-001	124150	SAN JACINTO	16	WATERWOOD MUD 1	0.1
14096-001	112747	TRINITY	17	AQUA UTILITIES INC	0.1
14787-001	27448	LEON	18	CITY OF NORMANGEE	0.1
14838-001	129895	GRIMES	19	CITY OF BEDIAS	0.095
12454-001	88862	POLK	20	AQUA TEXAS INC	0.08
13378-001	102849	MADISON	21	CITY OF MIDWAY	0.07
14261-001	119415	TRINITY	22	CAMP OLYMPIA INC	0.05
14582-001	127370	WALKER	23	SOUTH CENTRAL WATER CO	0.038
13147-001	98809	POLK	24	SHEFFIELD DAVID LEE	0.03
11310-001	24775	SAN JACINTO	25	TRINITY RIVER AUTHORITY OF TEXAS	0.025
13039-001	97063	SAN JACINTO	26	LAKE OAKS LANDING INC	0.025
14056-001	117331	SAN JACINTO	27	MONARCH UTILITIES I LP	0.025
14842-001	87203	TRINITY	28	TRINITY PINES CONFERENCE CENTER INC	0.025
13151-001	103250	POLK	29	FOUNTAIN LAKE OWNERS WSC	0.021
11644-001	59579	TRINITY	30	YOUNG MENS CHRISTIAN ASSN OF THE GREATER HOUSTON AREA	0.02
13547-001	106704	TRINITY	31	MONARCH UTILITIES I LP	0.02
11465-001	67415	POLK	32	PURE UTILITIES LC	0.015
11621-001	57657	POLK	33	PURE UTILITIES LC	0.015
14179-001	122513	SAN JACINTO	34	MONARCH UTILITIES I LP	0.015
13145-001	98752	SAN JACINTO	35	HOLIDAY HARBOR WATER/WASTE WATER SUPPLY CORP	0.013
11350-001	65064	TRINITY	36	FREEDOM SHORES INVESTMENT PARTNERSHIP LP	0.012
13354-001	101885	TRINITY	37	WHITE ROCK ESTATES PROPERTY OWNERS CIVIC ASSN	0.01
13637-001	75949	POLK	38	BEACON HOLDINGS CORP	0.0075
11831-001	72109	TRINITY	39	AZTEC COVE PROPERTY OWNERS ASSN	0.0075

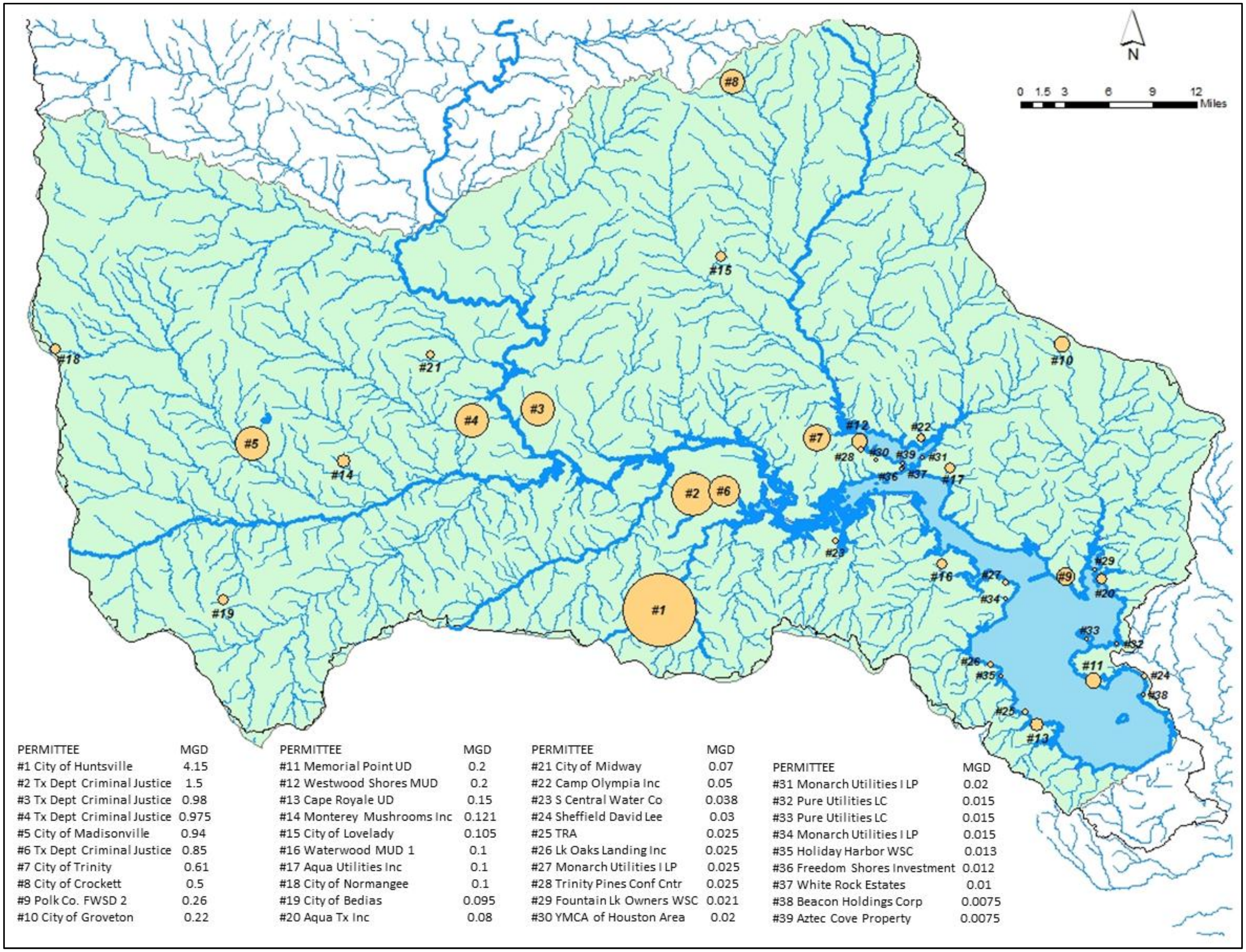

Figure 2-13 Permitted dischargers in the Lake Livingston watershed; bubbles and numbers indicate rank size.

Chapter 3
Data Development and Analysis Methods

Water Quality Data Inventory and Dataset Management

A full dataset of reported water quality data collected in the study area was developed by TRA in the spring of 2012 containing records from 1968 – 2011 for Segments 0803, 0804, 0805 and associated tributaries. The dataset contained records from 132 stations covering 1,438 water quality parameters (Figures 3-1–3-4). There were a total of 15,496 unique records with up to 170 parameters per record. Grooming this enormous dataset into a size useful for analysis required multiple steps:

1) **Station selection**
   Stations were selected according to their location and the robustness of their data:
   a) The number of years containing data, and
   b) Relevance of the stations' parameters to the water quality concerns of the watershed.
   Thirty-five stations were retained.
2) **Parameter selection and integration**
   a) The 1,438 water quality parameters were reduced to those parameters of greatest relevance to this study and for which adequate data existed to allow meaningful analyses. Generally the focus was on forms of nutrients, dissolved oxygen, water temperature, sulfate, *E. coli* and pH.
   b) Some parameters were integrated following unit conversion. For example, water temperature in degrees Fahrenheit was converted to degrees centigrade and integrated with values directly reported in degrees centigrade.
   c) Other parameters were merged that were deemed equivalent for the purposes of this report.
   Consolidating parameters produced a dataset with higher *n* for each parameter and reduced the total number of parameters used in analyses, an important benefit given the complexities of the dataset.
   Fifteen parameters most pertinent to the water quality of Lake Livingston were retained (see Table 3-1).
3) **Redundant records by sample depth**
   Records from the same station, date and depth had their values averaged to produce a single value for each constituent at a single station-date-depth. This was necessary to clean up redundant data and enable analyses that required a single value per station-day.
4) **Surface sample isolation**
   Many records from Lake Livingston stations represented depths greater than 0.5 ft. Although non-surface samples were retained for stratification investigations, they were removed for all other analyses which examined only surface samples.

The final dataset of 15 water quality parameters for analyses covered 35 stations for years 1970 – 2011 (Tables 3-2–3-4). Detailed information about the selected stations is presented in Table 3-5.

Further sub-setting for different purposes is described in the methods section and within each analysis in the Results and Discussion and Loading chapters of this report (4 and 5, respectively).

Table 3-1 Key water quality parameters given priority in this report following analysis of data availability across time and space and relevance to primary water quality concerns in Lake Livingston.

Water Quality Parameter	**Units**	**Abbreviation**
Ammonia	mg/L	NH_3
Total Kjeldahl Nitrogen	mg/L	TKN
Nitrate	mg/L	NO_3
Nitrite + Nitrate	mg/L	NO_{23}
Orthophosphate Phosphorus	mg/L	OP
Total Phosphorus	mg/L	TP
Chlorophyll-a	µg/L	Chl-a
Sulfate	mg/L	SO_4
Escherichia coli	colonies/100mL	*E. coli*
Total Suspended Solids	mg/L	TSS
5-day biochemical oxygen demand	mg/L	BOD_5
Fecal Coliform	colonies/100mL	Fcoli
pH	S.U.	pH
Alkalinity	mg/L as $CaCO_3$	Alky
Water Temperature	°C	WaterT

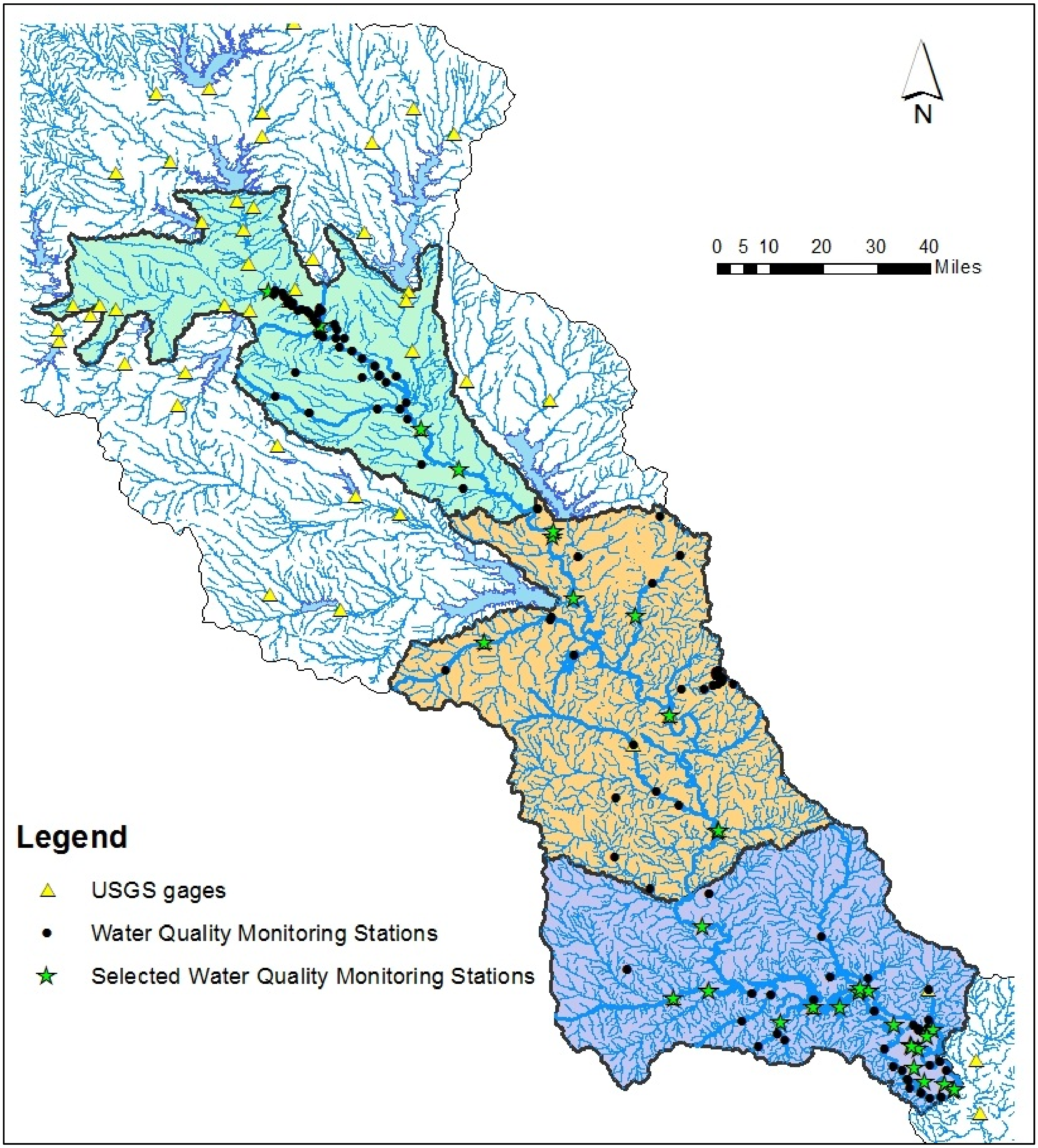

Figure 3-1 TCEQ water quality and USGS stations Segments 0805, 0804 and 0803.

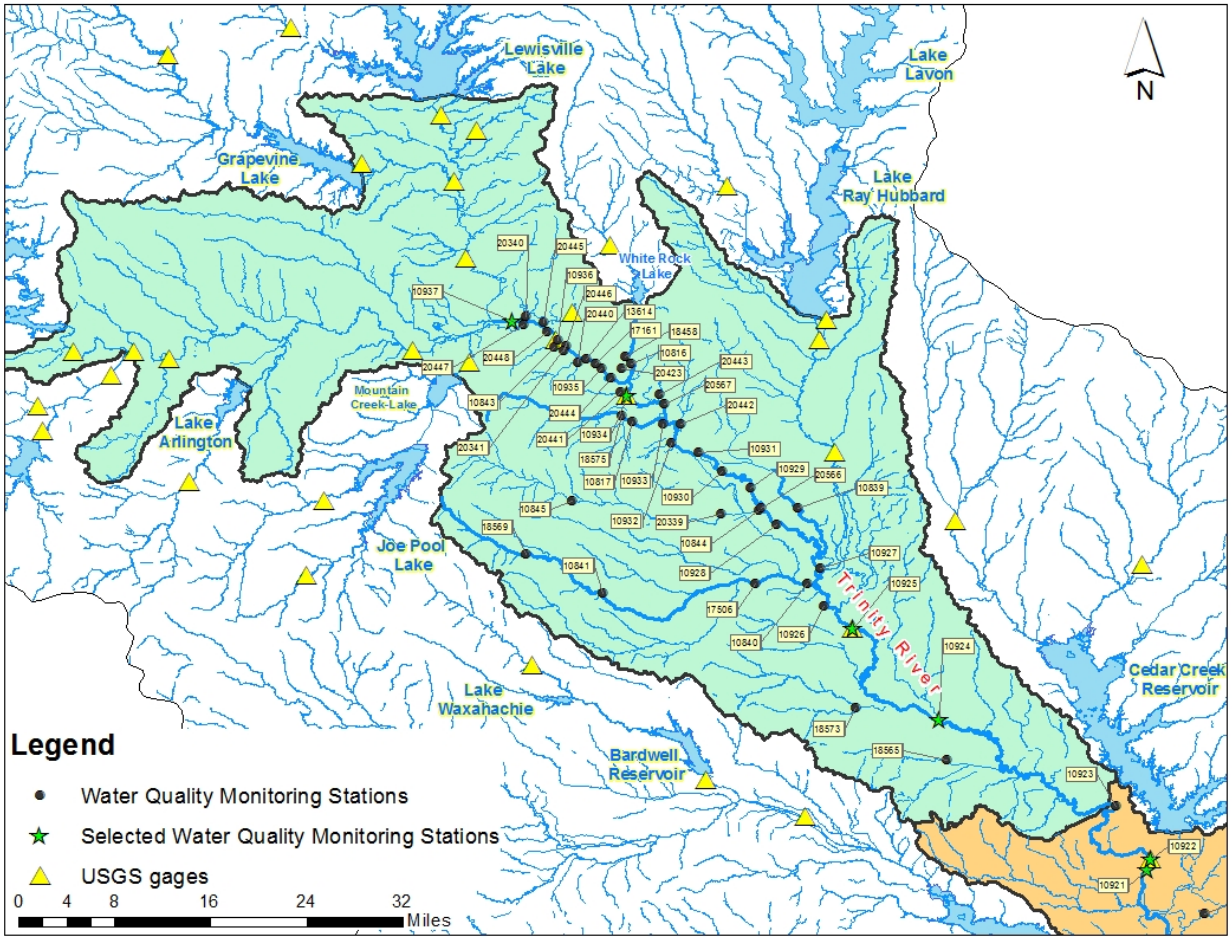

Figure 3-2 TCEQ water quality and USGS gaging stations, Segment 0805.

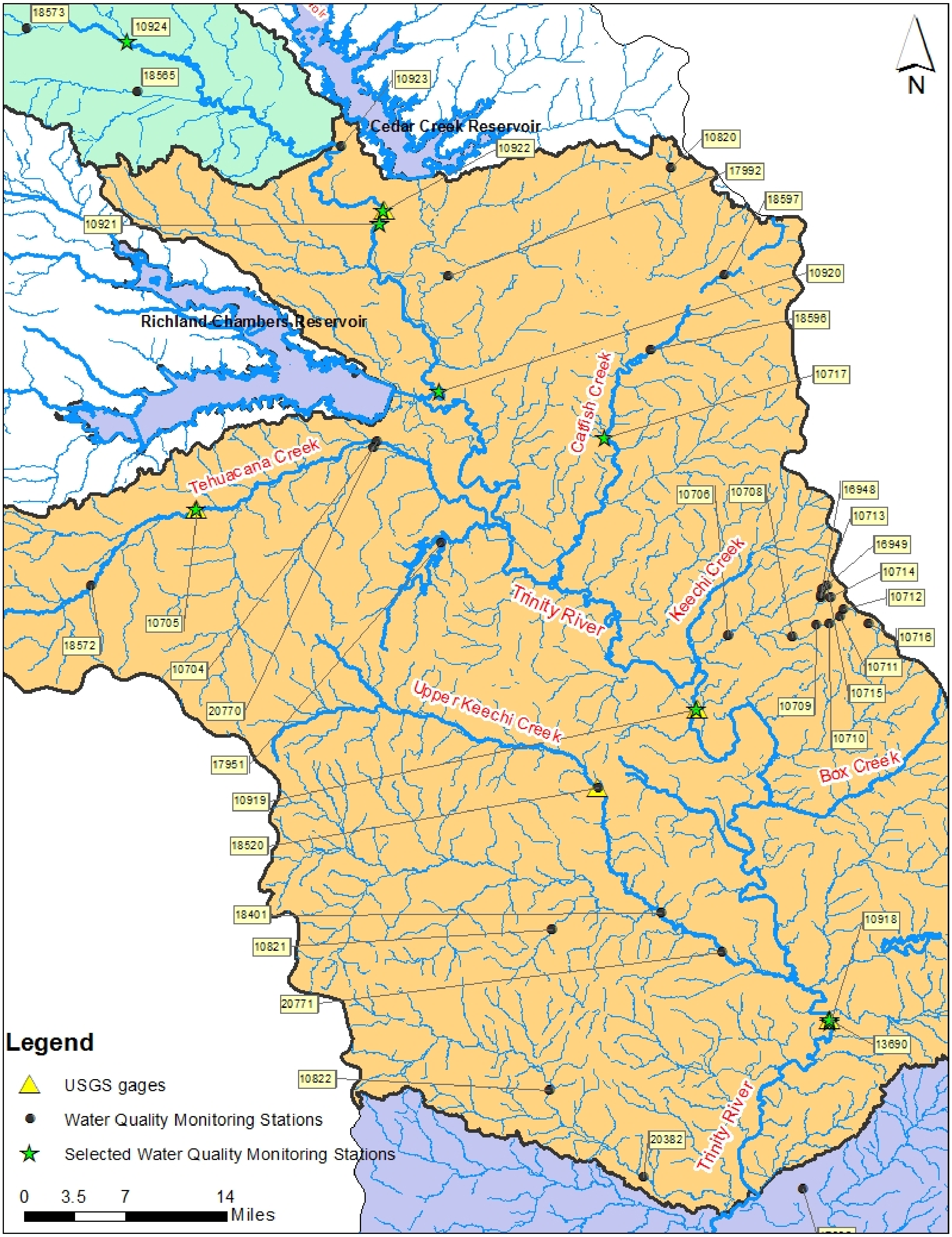

Figure 3-3 TCEQ water quality and USGS gaging stations, Segment 0804.

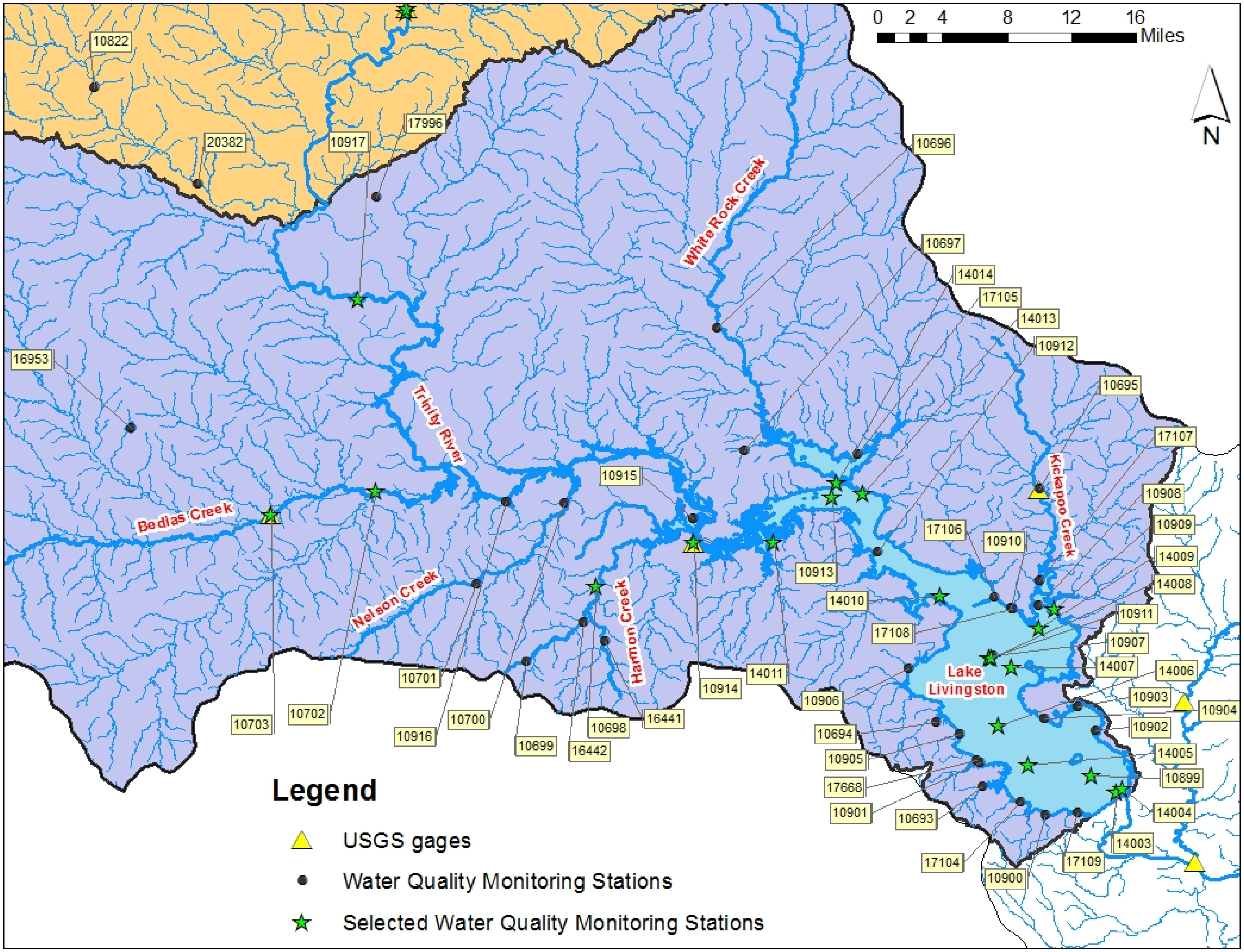

Figure 3-4 TCEQ water quality and USGS gaging stations, Segment 0803.

Table 3-2 Number of records containing key parameters by station and year for Segments 0805 and 0804 (1970 – 2011). Data from all depths included; 2011 a partial year of record; darker shades indicate more records.

System	***Trinity River***										
AU	0805_04	0805_03	0805_02	0805_01	0804_07			0804_04	0804_01		
Station	**10937**	**10934**	**10925**	**10924**	**10922**	**10921**	**10920**	**10919**	**13690**	**10918**	***TOTAL***
1970		12								12	24
1971		14	4			4				12	34
1972		13	12			12	11	11		12	71
1973		12	12			12	12	12		13	73
1974		15	12			9	10	10		11	67
1975		18	13			13	6	8		22	80
1976		13	12			12	3	4		20	64
1977		11	12			12	1	4		13	53
1978		11	11			11	1	4		13	51
1979		11	12			12	1	8		12	56
1980		12	12			11		13		14	62
1981		13	13			13		12	1	11	63
1982	2	21	20	2	2	15		13	6	11	92
1983	1	18	17	2	1	12		10	6	11	78
1984		16	16	1		13	2	15	5	11	79
1985		18	11	2		13	3	16	7	13	83
1986		18	13	9		13	7	13	6	18	97
1987		16	16	14	1	16		12	7	6	88
1988		23	18	7		14	2	12	17		93
1989		12	12	6		6		9	17		62
1990		10	9	5		6		7	17		54
1991		9	10	4		6		3	16		48
1992		9	10	4		5		4	18		50
1993		14	8	5		5		4	18		54
1994		14	8	2		4		4	20		52
1995		10	6					4	18		38
1996		7	6	1				4	18		36
1997		12	5	5		1		4	18		45
1998	1	12	5	8		8		8	17		59
1999	4	12	6	3		3	10	13	17		68
2000	7	14	13	4		4	2	11	24		79
2001	13	16	21	8	8	6		9	17		98
2002	13	32	26	3	20	2	1	15	18	1	131
2003	12	28	17		12			12	17		98
2004	12	20	19		12			12	18		93
2005	37	41	42	26	12			12	18		188
2006	14	21	19	4	12			12	18		100
2007	9	27	13		9			9	16		83
2008	5	23	11	2	4			4	16		65
2009	4	22	5		4			4	18		57
2010	4	18	9		4			4	17		56
2011	1	1	1		1			1			5
TOTAL	139	669	517	127	102	273	72	346	446	236	***2927***

Table 3-3 Number of records containing key parameters by station and year for tributary segments to Segments 0803 and 0804 (1970 – 2011). Data from all depths included; 2011 a partial year of record; darker shades indicate more records.

System	*Tributaries*								
AU	0804F_01	0803G_01	0803F_02	0803F_01	0803E_01		0803B_01	0803A_01	
Station	**10705**	**10717**	**10703**	**10702**	**10701**	**10700**	**10696**	**10698**	***TOTAL***
1970				4					4
1971				5				1	6
1972				17				11	28
1973				15				12	27
1974				11				11	22
1975				6			8	17	31
1976				3			12	14	29
1977				1		8	12	13	34
1978				1		10	10	11	32
1979				6		11	11	12	40
1980				7	8		6	12	33
1981	2			8	10		2	12	34
1982	6			6	12			12	36
1983	8			10	10			10	38
1984	7		8	11	11			13	50
1985	2		19	12	8			8	49
1986	3		18	12	3			4	40
1987	1		9	5	1			2	18
1988	1	2	6	3	3	1		5	21
1989		3			1	3		4	11
1990	1				2	1		2	6
1991	7	1			2	2		4	16
1992	5	4				4		4	17
1993	6	3	8			1		1	19
1994	6	1	13					1	21
1995	6		9	1	1	1	6	1	25
1996	5			1	1	1	1	6	15
1997	7			1	2		1	3	14
1998	5			1	1	1		1	9
1999	6	1		1	1	1		1	11
2000	4		1	1	1	1	2	2	12
2001	7			1			1	1	10
2002	5	1	2	1			1	2	12
2003	6	12	1	1	1	1		3	25
2004	8	9	1	1	1	1	1	2	24
2005	4	9	2	1	1	1	1	1	20
2006	3	14		1	1	1		1	21
2007	7	9		1		1	1	1	20
2008	6	5					1	1	13
2009	2	5		1		1	2	2	13
2010	4	10		1		1	2	2	20
2011		1							1
TOTAL	140	90	97	158	82	53	81	226	***927***

Table 3-4 Number of records containing key parameters by station and year for Segment 0803 (1970 – 2011). Data from all depths included; 2011 a partial year of record; darker shades indicate more records.

System	*Lake Livingston*																	
AU	0803_11	0803_10	0803_09	0803_08	0803_07		0803_06		0803_05		0803_04		0803_03	0803_02	0803_01			
Station	**10917**	**10914**	**14011**	**14014**	**10913**	**14013**	**14010**	**10911**	**10909**	**14009**	**14008**	**14007**	**14006**	**14005**	**10899**	**14004**	**14003**	***TOTAL***
1970		6													1			7
1971		13																13
1972	12	16						11										39
1973	12	13						12										37
1974	9	43						42										94
1975	5	43			52			50	32						83			265
1976	24	54			54			53	35						84			304
1977	18	41			39			50	30						70			248
1978	19	56			57			62	32						103			329
1979	15	47			56			56	28						85			287
1980	17	38			58			55	28						80			276
1981	15	33			44			48	32						68			240
1982	16	35			44			47	23						73			238
1983	13	28			25			25	13						60			164
1984	15	18			21			16	11						36			117
1985	16	25			27			28	15						42			153
1986	18	21			19			22	13						54			147
1987	8	21			21			19	18						37			124
1988	18	25			18			16	11						58			146
1989	14	22			21			21	6						63			147
1990	12	33			53			53	27						104			282
1991	11	24			26			30	16						69			176
1992	12	14			12			15	7						48			108
1993	11	67	10	10	15	12	14	16	8	8	13	6	13	14	40	12	16	285
1994	12	36	10	10	13	11	14	17	10	8	14	6	13	14	25	12	16	241
1995	12	23	10	10	2	12	14	2	1	8	13	6	13	14	24	12	16	192
1996	12	17	5	5	2	11	13	2		7	11	6	12	13	25	11	16	168
1997	12	22	10	9	2	11	13	2	1	8	12	6	12	13	23	13	17	186
1998	12	22	9	9	5	10	12	5	3	6	12	6	12	13	15	13	15	179
1999	12	29	9	8	12	10	12	13	12	7	9	6	12	12	20	13	16	212
2000	12	24	9	8	8	10	12	8	7	6	11	6	12	12	16	12	16	189
2001	12	25	10	10	6	10	6	6	5	7	12	6	12	13	12	12	16	180
2002	12	23	10	9	5	10	12	5	5	7	12	7	13	14	14	12	16	186
2003	12	22	10	10	5	10	12	28	4	8	12	7	13	13	40	12	16	234
2004	12	23	10	13	4	10	11	10	4	8	12	7	16	17	19	11	15	202
2005	12	18		4	2	4	3	2	2	3	4	5	5	8	9	5	5	91
2006	12	14		2	4			4	4			2	2	2	6			52
2007	12	12			2			2	2			1	1		3			35
2008	12	12			2			2	2						5			35
2009	12	12			3			3	3						3			36
2010	11	33		21	4			4	4			22	53	35	16			203
2011																		0
TOTAL	513	1103	112	138	743	131	148	862	454	91	147	105	214	207	1533	150	196	***6847***

Table 3-5 Detail of stations selected for analyses and their collocated USGS gages in Segments 0803, 0804, 0805 and several tributaries.

Station	First Record	Last Record	Years	River Mile[a]	Seg_AU	USGS	First Record [b]	Last Record	TCEQ Description
Lake Livingston									
14003	24-Feb-93	17-Aug-05	13	116.5	0803_01				LAKE LIVINGSTON SITE AC
14004	24-Feb-93	17-Aug-05	13	117	0803_01				LAKE LIVINGSTON SITE AL
10899	16-Jul-70	27-Oct-10	37	118	0803_01				LK LIVINGSTON NEAR DAM
14005	24-Feb-93	16-Nov-10	15	128	0803_02				LAKE LIVINGSTON SITE BC
14006	24-Feb-93	16-Nov-10	16	133	0803_03				LAKE LIVINGSTON SITE CC
14007	24-Feb-93	30-Nov-10	16	138	0803_04				LAKE LIVINGSTON SITE DL
14008	24-Feb-93	17-Aug-05	13	139.5	0803_04				LAKE LIVINGSTON SITE DC
10911	7-Feb-72	27-Oct-10	39	139.6	0803_06				LK LIVINGSTON NEAR US HWY 190
14009	24-Feb-93	17-Aug-05	13	141	0803_05				LAKE LIVINGSTON SITE EC
10909	15-Jan-75	27-Oct-10	35	143	0803_05				LK LIVINGSTON IN KICKAPOO BAY
14010	24-Feb-93	17-Aug-05	13	144.5	0803_06				LAKE LIVINGSTON SITE FC
14013	25-Feb-93	18-Aug-05	13	153.5	0803_07				LAKE LIVINGSTON SITE GC
14014	25-Feb-93	30-Nov-10	15	155	0803_08				LAKE LIVINGSTON SITE HC
10913	15-Jan-75	27-Oct-10	36	155.5	0803_07				LK LIVINGSTON IN MAIN CHANNEL
14011	25-Feb-93	25-Aug-04	12	161	0803_09				LAKE LIVINGSTON SITE IC
10914	31-Jul-70	29-Nov-10	41	167	0803_10	8066000[c]	11-May-95	14-May-12	LAKE LIVINGSTON AT SH 19
10917	7-Feb-72	29-Nov-10	39	212	0803_11				LAKE LIVINGSTON AT SH 21
Trinity River									
10918	11-Sep-68	30-Jul-02	21	244.3	0804_01				TRINITY RIVER AT SH 7
13690	16-Oct-81	29-Nov-10	30	244.5	0804_01	8065350	1-Jan-70	14-May-12	TRINITY RIVER UPSTRM OF SH 7
10919	7-Feb-72	16-Feb-11	40	291	0804_04	8065000	1-Jan-70	14-May-12	TRINITY RIVER AT US HWY 79
10920	8-Feb-72	30-Jul-02	16	351	0804_07				TRINITY R DOWNSTREAM OF US 287
10921	14-Sep-71	11-Jul-02	30	368.5	0804_07	8062700	1-Jan-70	14-May-12	TRINITY R DOWNSTREAM OF SH 31
10922	14-Sep-82	16-Feb-11	14	369.5	0804_07				TRINITY RIVER AT SH 31
10924	14-Sep-82	6-Aug-08	23	408.5	0805_01				TRINITY RIVER AT FM 85
10925	14-Sep-71	16-Feb-11	41	423.5	0805_02	8062500	1-Jan-70	14-May-12	TRINITY R DOWNSTREAM OF SH 34
10934	11-Sep-68	15-Feb-11	44	463.5	0805_03	8057410[d]	1-Jan-70	14-May-12	TRINITY R AT SOUTH LOOP SH 12
10937	14-Sep-82	22-Feb-11	16	476	0805_04				TRINITY R AT N WESTMORELAND

Table 3-5 *Cont.*

Station	First Record	Last Record	Years	River Mile	Seg_AU	USGS	First Record	Last Record	TCEQ Description
Tributaries									
10696	5-Feb-75	23-Jun-10	19	--	0803B_01				WHITE ROCK CK DSTM OF CEDAR CK
10698	23-Sep-71	23-Jun-10	40	--	0803A_01				HARMON CK UPSTRM FROM OTTER RD
10700	26-May-77	20-Jul-10	21	--	0803E_01				NELSON CREEK AT FM 3478
10701	26-Feb-80	26-Sep-06	22	--	0803E_01				NELSON CREEK DWNSTRM OF FM 247
10702	14-May-69	20-Jul-10	35	--	0803F_01				BEDIAS CREEK AT BRIDGE FM 247
10703	25-Apr-84	27-Dec-05	13	--	0803F_02	8065800	1-Jan-70	14-May-12	BEDIAS CREEK DOWNSTRM OF US 75
10705	13-Oct-81	29-Jul-10	29	--	0804F_01	8064700	1-Jan-70	14-May-12	TEHUACANA CR DWNSTRM OF SH 75
10717	16-Aug-88	12-Apr-11	17	--	0803G_01				CATFISH CREEK IN ENGLING WMA

[a] As measured from the dam moving upstream.
[b] Queried only 1970 forward.
[c] Gage height data only.
[d] Gap in data from 01-Oct-99 to 30-Sep-2002.

Data Analysis Methods

To address the data analysis and assessment objectives, a variety of methods were used to evaluate water quality and loading characteristics. Chapter 4 presents the results of the water quality analyses with regard to trends and general conditions, while Chapter 5 presents estimates of loadings to Lake Livingston as well as an evaluation characterizing these loadings with regard to flow and temporal patterns.

The analysis of water quality data was broken into five sections, which largely build one upon the next as follows:

1) Historical long-term trends (1970-2011),
2) More recent or shorter-term trends (1991-2011)
3) Spatial and temporal variability in water quality conditions between stations and by month,
4) Patterns in water quality with regard to seasonality and flow and
5) Longitudinal patterns along the Trinity River and within Lake Livingston.

Water quality analyses focused on three major groupings of stations as outlined in Table 3-5. These involved monitoring stations along the mainstem of the Trinity River, stations on tributaries, and stations on Lake Livingston. Plots by season were also used to aid in evaluating the impact of seasonality on variations in parameter values.

To assess long-term trends of historical water quality, simple liner regression with the slope of significant (alpha = 0.05) regression lines used to indicate upward or downward trends in the concentration of individual water quality parameters. Long-term trends were defined for data collected between 1970 and 2011.

Correlation analysis and evaluation of more recent trends focused on monitoring data collected between 1991 and 2011. These data were restricted to beginning January 1, 1991 due to changes in flow along the Trinity River, particularly increases in baseflow associated with increasing WWTF discharges from the steadily increasing population in the DFW area (Figure 2-4).

Analysis of the more recent data (1991-2011) then took five broad approaches. The first approach was to evaluate trends for the more limited time period. This trend analysis, similar to the long-term trend evaluation, focused on the slope of linear regression models to indicate significant increasing or decreasing concentrations of parameters. The second approach involved the development of boxplots that evaluated water quality data spatially by station in comparison to appropriate screening levels and criteria. The third approach merged both temporal and spatial components by presenting the 75th percentile of parameter values by month in comparison to variation in hydrologic parameters. The fourth approach focused on potential temporal patterns with regard to flow and seasonality, as influenced primarily by temperature, by using cluster analysis, seasonal boxplots, and correlation analysis. The fifth approach evaluated median values for stations in a longitudinal pattern from upstream to downstream along the Trinity River continuing to the dam within Lake Livingston.

This report contains many boxplots used to present spatial and temporal trends in water quality. Boxplots are effective visual tools for conveying the distribution of data at a location or time period. As the diagram in Figure 3-5 demonstrates, the mean, median, 1st and 3rd quartiles, upper and lower fences and outliers are all conveyed without creating a cluttered appearance. Normally distributed data results in a boxplot where the mean (black dot) lies atop the median line and the quartiles are approximately equidistant from the median. The example in Figure 3-5 illustrates a dataset that is skewed toward higher values.

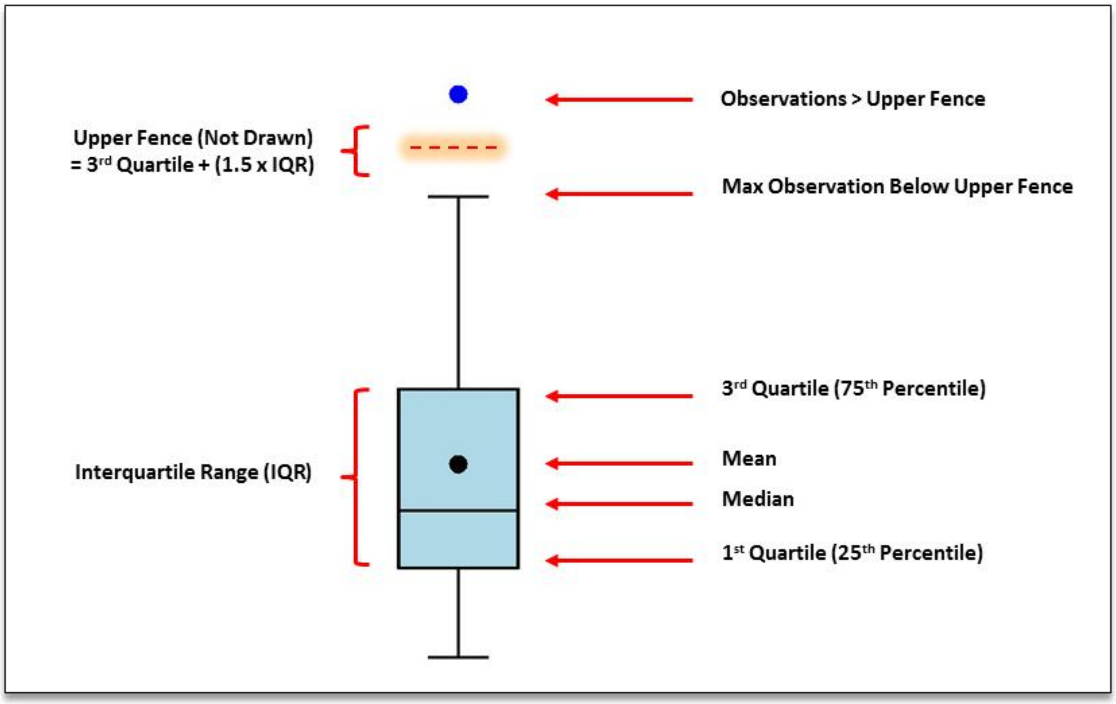

Figure 3-5 Diagram of boxplot components including mean, median, 1st and 3rd quartiles, outliers and the upper fence defined as the 3rd quartile plus 1.5 times the IQR.

For the loading analysis presented in Chapter 5, loadings to Lake Livingston were developed using the Load Estimator (LOADEST) FORTRAN program available from the USGS (2012). Loadings were developed for the Trinity River based on flow data from the USGS station 08065350 on the Trinity River at Crockett, Texas and water quality data from TCEQ station 13690. For other tributaries flowing into Lake Livingston, loadings were estimated using a drainage area ratio extrapolating from flow data from the USGS station 08065800 on Bedias Creek near Madisonville, Texas, with concentration data from TCEQ stations 10702 and 10703. Based on available data, loadings were calculated for the following ten parameters:

- BOD_5
- Chl-a
- *E. coli*
- NH_3
- NO_3
- OP

- TP
- Sulfate
- TKN
- TSS

Based on loading estimates from LOADEST, daily water quality concentrations were back-calculated with flow and used to evaluate patterns in modeled concentrations with flow and over time to aid in elucidating potential threats and sources to Lake Livingston. Details on how the LOADEST model was applied are presented in Chapter 5.

Chapter 4
Results and Discussion

Analysis of water quality trends and current conditions focused on 15 select water quality parameters (Table 3-1). These "key parameters" were chosen according to their relevance to the most pressing water quality concerns in Lake Livingston and its watershed and their spatial and temporal representation in the dataset.

A subset of these key parameters includes those for which criteria and screening levels have been established by the TCEQ (Table 4-1). In Lake Livingston the parameters of particular concern are those that frequently exceed criteria set by the state, i.e., pH, SO_4 and Chl-a (Station 10899), landing the lake on the 303(d) list or regularly exceed screening levels, i.e., NH_3, NO_3, OP, TP and Chl-a. The 2010 Guidance for Assessing and Reporting Surface Water Quality in Texas (TCEQ, 2010a) lists screening levels for NH_3, NO_3, OP, TP and Chl-a (Table 4-1). These screening levels were statistically derived by TCEQ from surface water quality monitoring (SWQM) data for the entire state and represent the 85th percentile values for each parameter in reservoirs and freshwater streams. Under TCEQ's biennial assessment of the State's water bodies, a concern for water quality is identified if a screening level is exceeded more than 20 percent of the time using the binomial method, based on the number of exceedances for a given sample size (TCEQ, 2010a).

It is impractical to include in this report the full number of trend graphs, boxplots, etc., for each of the 15 key parameters and 35 select stations, so only selected graphs are presented. In some instances, trends that are similar among multiple water quality parameters are presented only for the one parameter that best illustrates the trend being discussed. The maps presented in Figures 4-1–4-3 highlight the 35 stations selected for analysis in this report.

Table 4-1 Summary of criteria and screening levels for select parameters in Lake Livingston (Segment 0803) and the Trinity River (Segments 0804 & 0805). See Table 2-1 for additional details.

Parameter	Criteria By Segment			Parameter	Screening Level	
	0803	0804	0805		Reservoir	Freshwater Stream
pH	6.5 – 9.0	6.5 – 9.0	6.5 – 9.0	NH_3 (mg/L)	0.11	0.33
SO_4 (mg/L)	50[c]	150	175	NO_3 (mg/L)	0.37	1.95
Chl-a (µg/L)	22.96[a]	--	--	OP (mg/L)	0.05	0.37
E. coli (Colonies /100mL)[b]	126	126	126	TP (mg/L)	0.2	0.69
				Chl-a (µg/L)	26.7	14.1

[a] Station 10899 in Lake Livingston.
[b] Geometric mean
[c] The present applicable sulfate criterion is 50 mg/L; the 2010 Texas Surface Water Quality Standards has the criterion increased to 60 mg/L and this higher value is not approved by USEPA as of Oct. 2012.

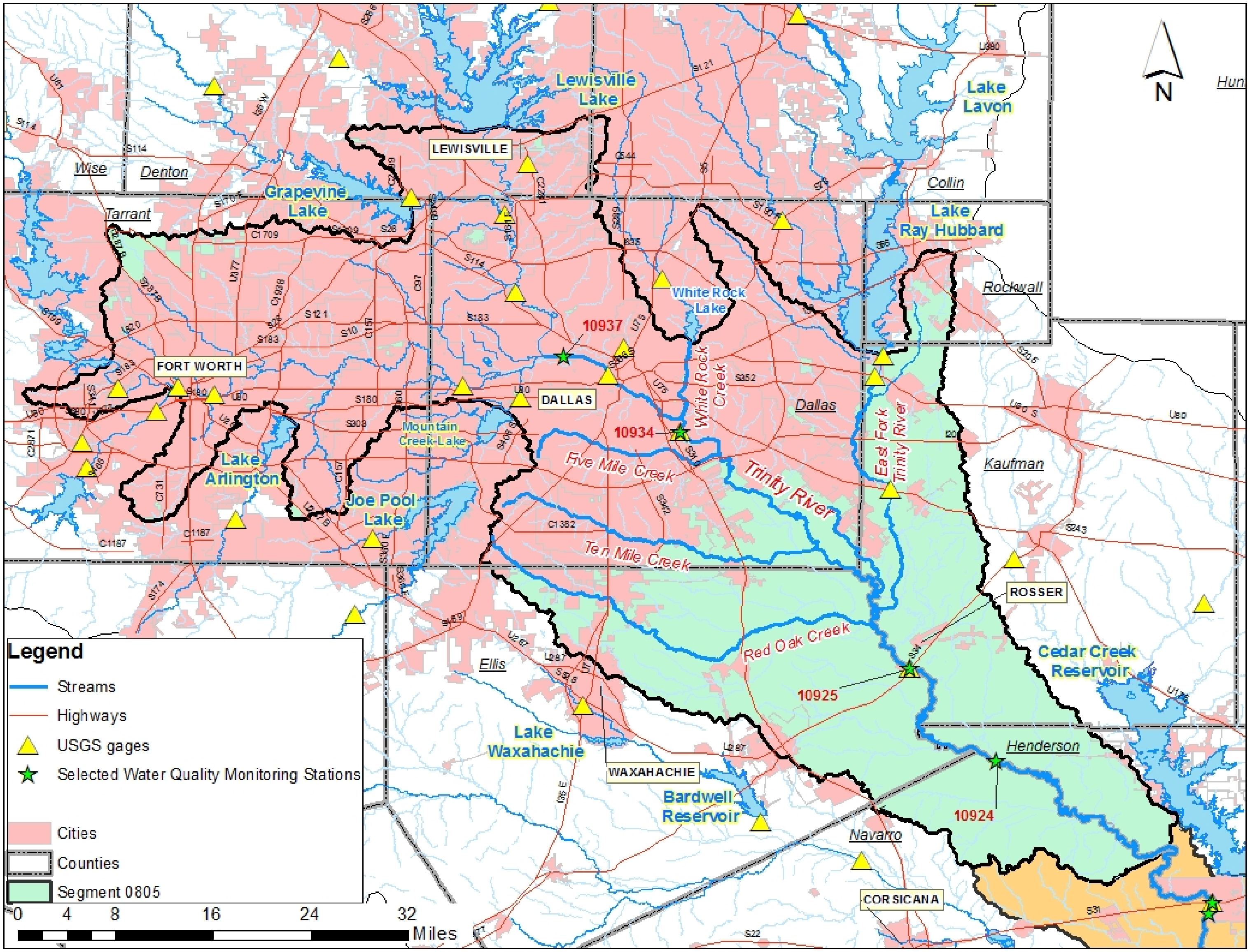

Figure 4-1 Water quality sampling stations selected for analysis in Segment 0805 and associated tributaries.

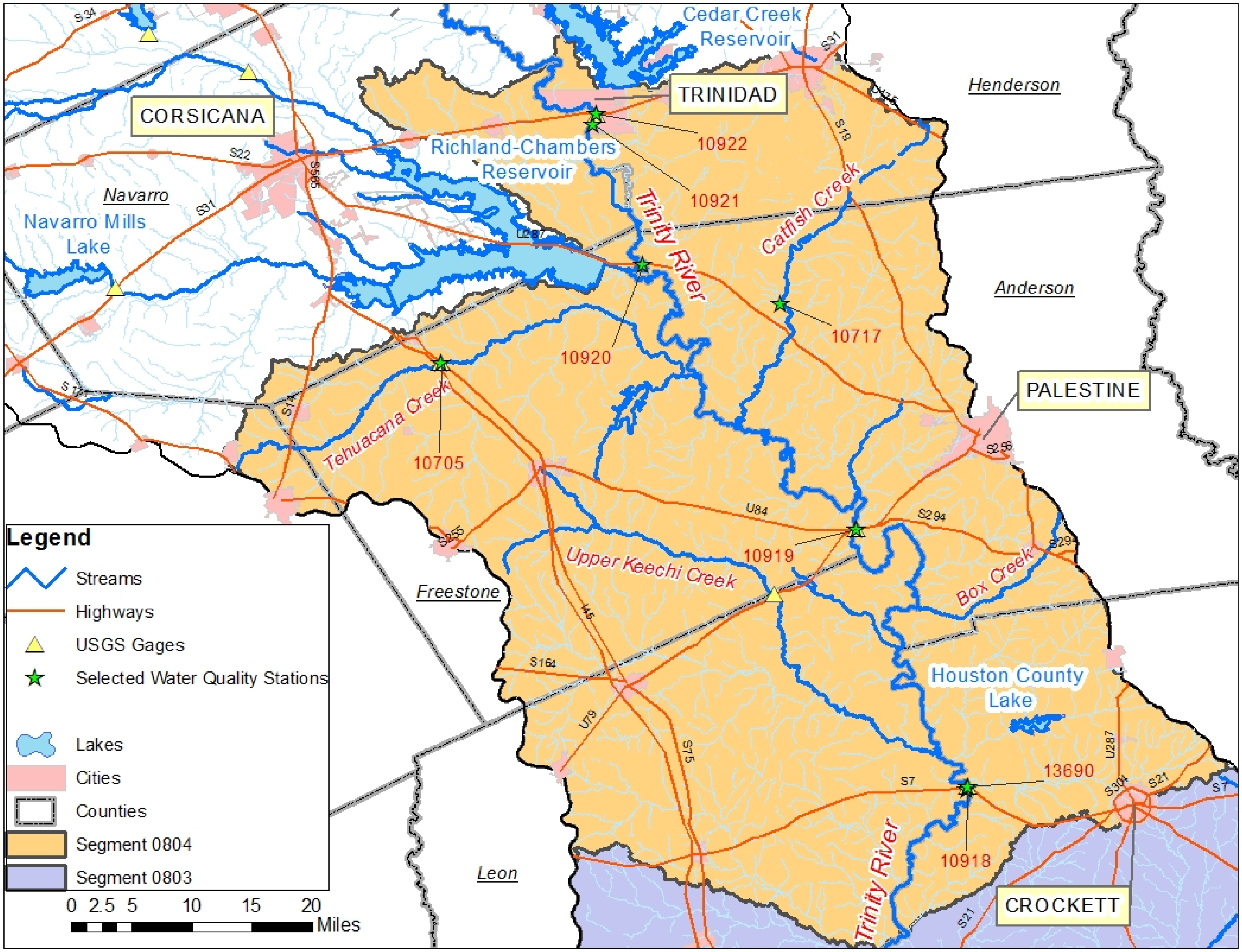

Figure 4-2 Water quality sampling stations selected for analysis in Segment 0804 and associated tributaries.

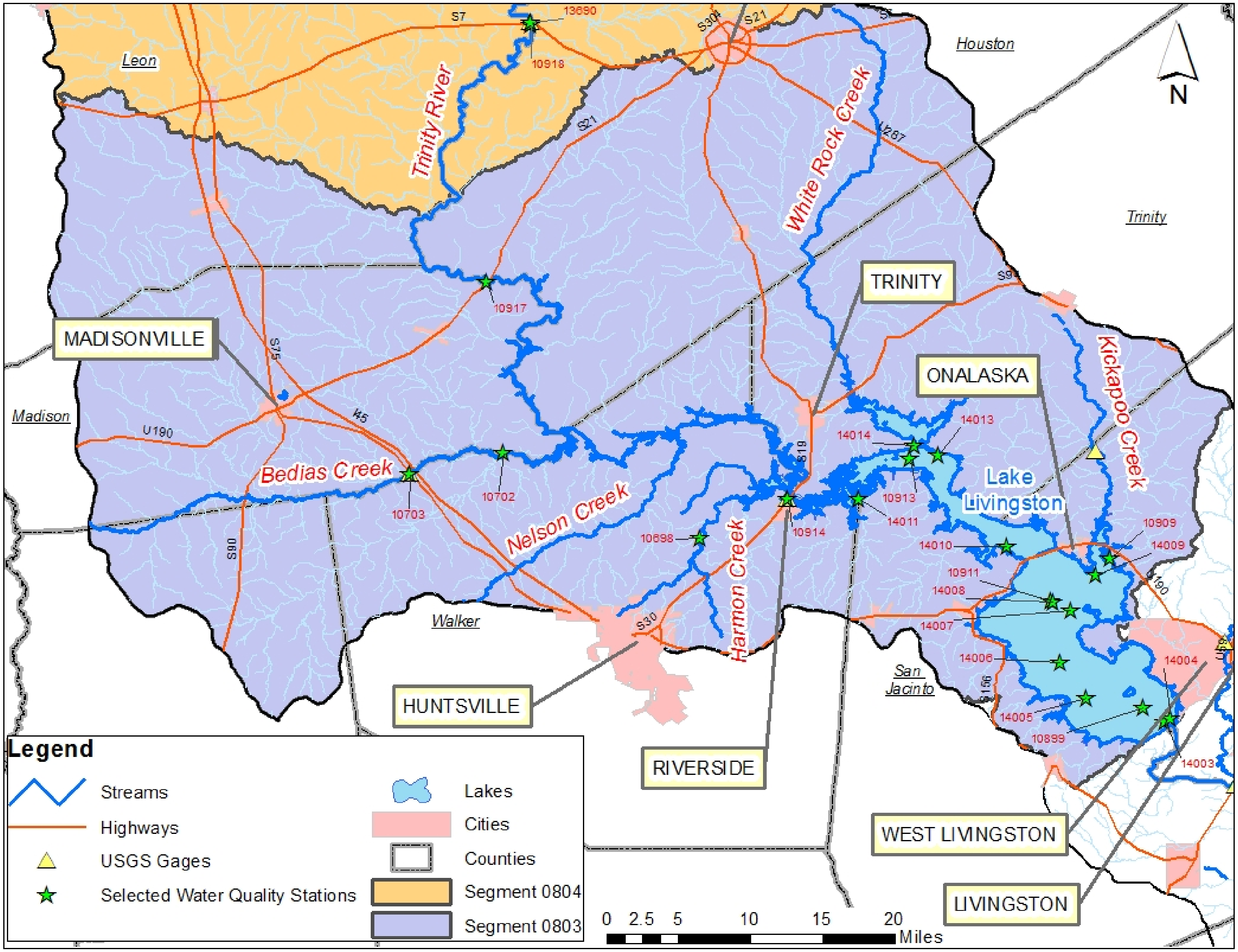

Figure 4-3 Water quality sampling stations selected for analysis in Segment 0803 and associated tributaries.

The following analyses are organized to examine trends; first at broad spatial and temporal scales, then narrow down to recent trends and conditions in Lake Livingston. For the long-term and more recent trend analyses and also spatial analyses, the results are presented by three groupings or station types: 1) Trinity River stations, 2) tributary stations, and 3) Lake Livingston stations. While more difficult to do for the tributary stations, within these three groupings the results are presented in tables from most upstream station on the left to most downstream on the right.

A. Trinity River (see Figures 4-1 & 4-2)
   - Station 10934 - Trinity River at South Loop 12 (Dallas area)
   - Station 10925 – Trinity River at SH 34 (northeast of Ennis)
   - Stations 10921 & 10922 – Trinity River at SH 31 ((at Trinidad)
   - Station 10919 – Trinity River at US Highway 79 (southwest of Palestine)
   - Station 10918 & 13690 – Trinity River at SH 7 (west of Crockett)

B. Tributaries (see Figures 4-2 & 4-3)
   - Station 10717 on Catfish Creek
   - Station 10795 on Tehuacana Creek
   - Stations 10702 & 10703 on Bedias Creek
   - Station 10698 on Harmon Creek

C. Lake Livingston Stations (see Figure 4-3)
   - Station 10917 – Lake Livingston at SH 21 (northeast of Madisonville)
   - Station 10914 – Lake Livingston at SH 19 (near Riverside)
   - Station 10913 – Lake Livingston in main channel
   - Station 10909 – Lake Livingston in Kickapoo Bay
   - Station 10911 – Lake Livingston near US Highway 190
   - Station 10899 – Lave Livingston in main body (near dam)

Historical Long-Term Trends in Water Quality Conditions

Analysis of long-term trends covered water quality data from 1970 – 2011 for primary stations in the Trinity River, major tributaries and Lake Livingston as listed and grouped above. Several time-series are presented below that group points (i.e., a water quality value obtained on a certain date) by season, wherein warm months include April – October and cool months include November – March. This seasonal scheme is reasonable according to water temperature trends that show distinct separation of warm- and cool-season temperatures (Figure 4-4). Tables of trend regression results across seasons are also presented for quantitative analysis of the direction and significance of the trends of the key parameters over time.

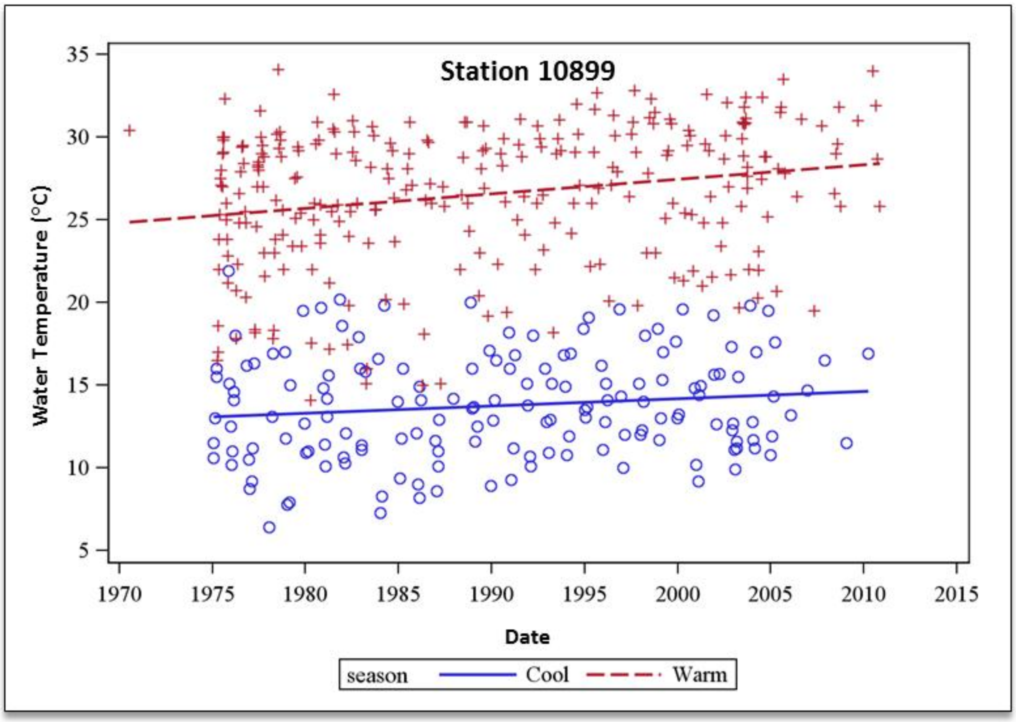

Figure 4-4 Temporal trends by season in Lake Livingston surface water temperature, 1970 – 2011, Station 10899.

Trinity River Stations

At Trinity River stations NH_3, TKN, TP, OP and BOD_5 concentrations all sharply declined beginning in the late 1980s and early 1990s (Table 4-2). These patterns are typified by the trend graphs of NH_3 and OP at Station 10934 (Figure 4-5). Sharp declines in these water quality parameters are most likely explained by two series of events – increased levels of treatment prescribed for WWTFs in the DFW area and bans on phosphorus in detergents. In the 1970s as the DFW area moved towards large regionalized WWTFs, there was also implemented advanced treatment requirements over the period of 1977-1983 followed by more stringent nitrification requirements (i.e., lower NH_3 concentration allowed in WWTF effluents) implemented in the mid-1980s (TRA, 2012). Also, in the early 1990s in response to eutrophication problems, bans on phosphorus in detergents were implemented across the United States making the availability of phosphorus in detergents more limited (Litke, 1999). While bans on phosphorus in detergents were not state-wide in Texas, most notably in June 1991 the City of Austin implemented a ban restricting phosphorus levels to 0.5 percent (Litke, 1999). These bans effectively resulted in reduced phosphorus in detergents even in non-targeted geographic areas as manufacturers opted nationwide for producing a single low-phosphorus formulation of their detergent brands rather than having different formulations by region of the country. These bans effectively reduced influent phosphorus to WWTFs with a commensurate reduction of phosphorus in their effluent.

Table 4-2 Direction and significance of long-term trends, 1970 – 2011, in the Trinity River (Segments 0804 & 0805). Non-significant trends indicated by "NS"; significant ("*"; $p \leq 0.05$) and strongly significant ("*"; $p \leq 0.001$) trends are highlighted yellow and orange, respectively; nd = no data.

	Trinity River ***(stations listed in upstream to downstream order from left to right)***									
	10934		**10925**		**10921 & 10922**		**10919**		**10918 & 13690**	
Parameter	*n*	Trend/Sig	n	Trend/Sig	n	Trend/Sig	n	Trend/Sig	n	Trend/Sig
NH_3	492	**- / ****	352	**- / ****	271	**- / ****	305	**- / ****	583	**- / ****
TKN	392	**- / ****	171	**- / ****	179	**- / ****	223	**- / ****	420	**- / ****
NO_3	269	**+ / ****	153	**+ / ****	90	+ / NS	178	- / NS	264	**+ / ****
NO_{23}	449	**+ / ****	273	**+ / ****	192	- / NS	260	**+ / ****	272	+ / *
OP	433	**- / ****	288	**- / ****	268	**- / ****	292	**- / ****	507	**- / ****
TP	487	**- / ****	278	**- / ****	270	**- / ****	282	**- / ****	457	**- / ****
Chl-a	288	**- / ****	205	- / *	188	- / *	281	- / NS	266	- / NS
SO_4	447	**- / ****	292	+ / NS	213	+ / NS	238	- / NS	567	- / NS
E. coli	111	+ / NS	114	- / NS	95	+ / NS	86	+ / NS	101	- / NS
TSS	197	+ / NS	117	+ / NS	115	+ / NS	239	+ / NS	466	- / NS
BOD5	101	**- / ****	154	**- / ****	94	**- / ****	13	- / NS	255	**- / ****
Fcoli	164	+ / NS	106	- / NS	95	+ / NS	200	- / NS	217	- / *
pH	594	**+ / ****	465	**+ / ****	356	**+ / ****	332	**+ / ****	647	**+ / ****
Alk	214	**- / ****	145	**- / ****	149	- / *	200	- / NS	512	**- / ****
WaterT	625	**+ / ****	475	+ / *	362	+ / *	339	+ / NS	675	+ / NS

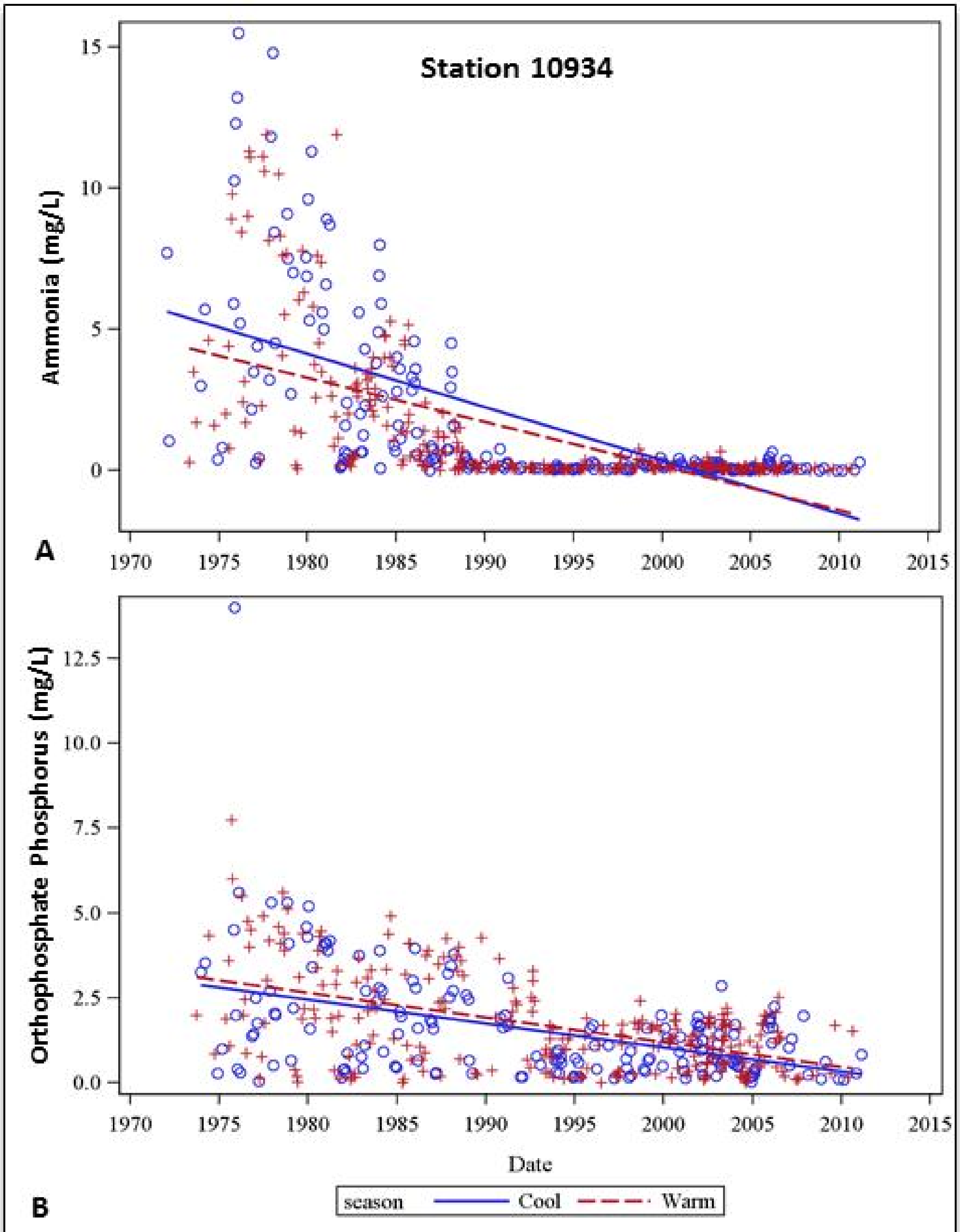

Figure 4-5 Temporal trends by season in NH_3 and OP, 1970 – 2011, Station 10934 (AU 0805_03).

Inorganic nitrogen as NO_3 and NO_{23} (Figure 4-6), in contrast, has steadily increased at the upper and lower stations of the Trinity River above Lake Livingston (Table 4-2). Note that NO_{23} was used instead of NO_3 in Figure 4-6 due to major time gaps in the NO_3 dataset at the selected stations. The NO_3 trends, based on limited data, approximated the trends in NO_{23}. Interestingly, pH has risen significantly at every Trinity station even as Chl-a and alkalinity have decreased in the upper stations. There is also no distinction between the warm and cool season values of pH for the Trinity River stations.

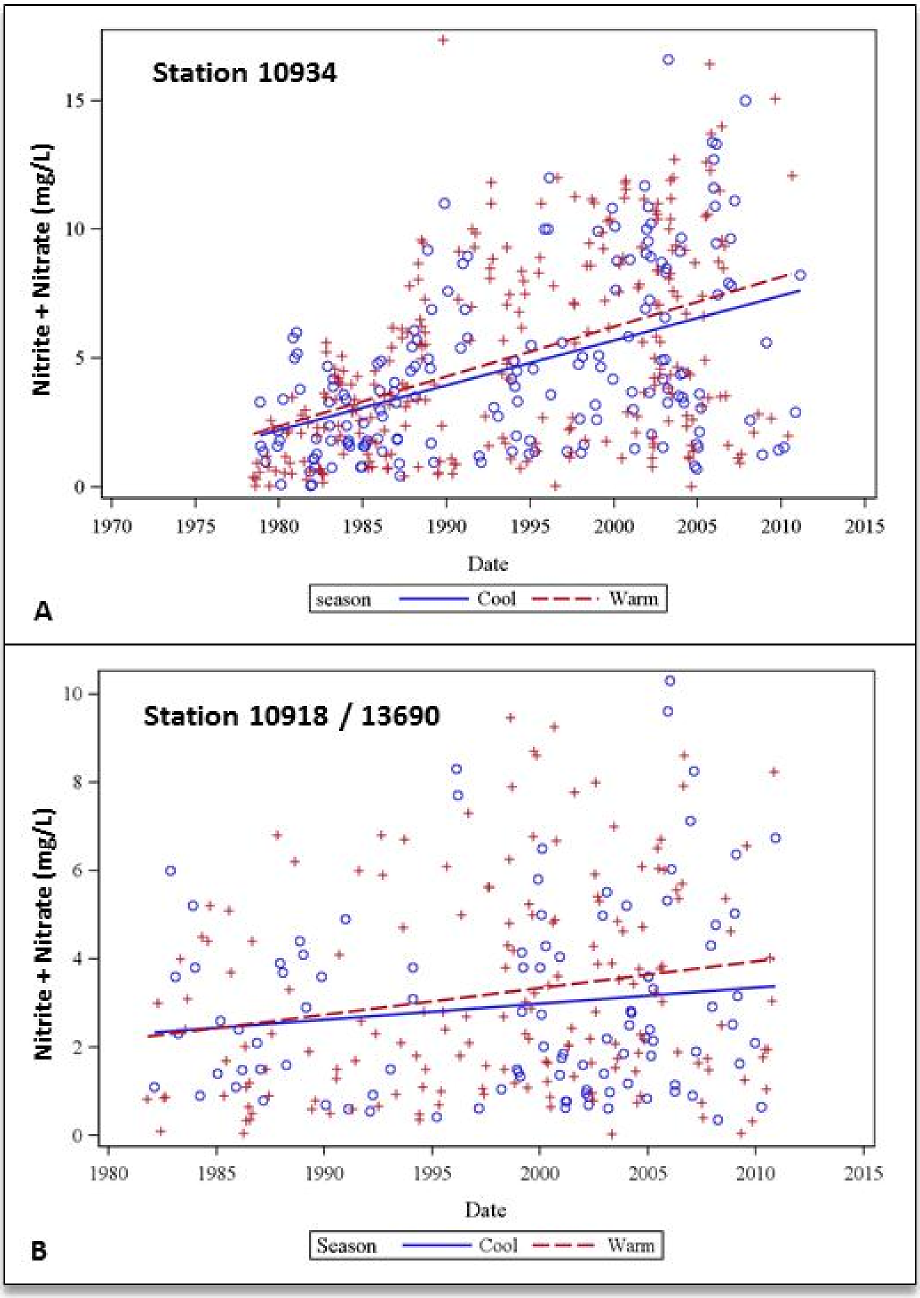

Figure 4-6 Temporal trends by season in NO_{23}, 1970 – 2011, Stations 10934 (A; AU 0805_03) and 10918/13690 (B; AU 0804_01).

Tributary Stations

Long-term trends for tributary stations were generally inconclusive with the exception of Harmon Creek (Station 10698) where NO_3 and SO_4 increased and NH_3, TKN, TP and Alky all decreased since 1970 (Table 4-3). Harmon Creek receives the City of Huntsville WWTF effluent. A likely explanation for the decreasing trends in some water quality constituents observed at Station 10698 is that higher levels of treatment have been implemented at the Huntsville WWTF over time. Both OP and TP increased over time in Bedias Creek, which could be an indicator of some wastewater influence from the City of Madisonville WWTF, although its discharge is small and occurs relatively far upstream of Stations 10702 and 10703 on a tributary to Bedias Creek. The City of Madisonville WWTF discharges into Town Branch, which flows into Caney Creek before reaching Bedias Creek.

Table 4-3 Direction and significance of long-term trends, 1970 – 2011, in select tributaries of Lake Livingston. Non-significant trends indicated by "NS"; significant ("*"; $p \leq 0.05$) and strongly significant ("*"; $p \leq 0.001$) trends are highlighted yellow and orange, respectively; nd = no data.

	Tributaries							
	10717 Catfish Cr.		**10705 Tehuacana Cr.**		**10702 & 10703 Bedias Cr.**		**10698 Harmon Cr.**	
Parameter	n	Trend/Sig	n	Trend/Sig	n	Trend/Sig	n	Trend/Sig
NH_3	41	- / NS	100	**- / ****	160	- / *	204	**- / ****
TKN	35	- / NS	15	- / NS	105	- / *	130	**- / ****
NO_3	19	- / NS	20	+ / NS	99	+ / *	149	**+ / ****
NO_{23}	40	- / NS	93	+ / NS	40	- / NS	16	- / NS
OP	40	- / *	100	- / NS	144	+ / *	184	- / *
TP	43	- / NS	21	- / NS	154	+ / *	192	**- / ****
Chl-a	39	+ / NS	6	+ / NS	79	- / NS	145	- / *
SO_4	44	+ / NS	125	- / NS	187	+ / NS	174	**+ / ****
E. coli	29	- / NS	nd	Nd	11	+ / NS	15	+ / NS
TSS	43	+ / NS	99	- / NS	123	- / NS	204	- / *
BOD_5	nd	nd	91	+ / NS	63	- / NS	83	+ / *
Fcoli	10	+ / NS	6	- / NS	95	+ / *	133	- / NS
pH	47	- / NS	116	- / *	187	+ / NS	220	- / NS
Alky	42	- / *	30	+ / NS	142	+ / *	197	**- / ****
WaterT	47	- / NS	137	+ / NS	209	+ / NS	222	- / NS

Lake Livingston Stations

Trends in Lake Livingston followed those in Trinity River and Harmon Creek wherein NH_3, TKN, OP and TP all decreased significantly (Table 4-4) with a dramatic drop around 1990, which are exemplified by the trend graphs of NH_3 at the uppermost (10917) and lowermost (10899) lake stations (Figure 4-7). An upward trend in lake NO_3 (Figure 4-8) and NO_{23} was not as distinguishable as in the Trinity River, although the most upstream lake stations, 10917 and 10914, exhibited significant positive trends. pH increased significantly at all lake stations. Chl-a only showed a strongly significant increase at Station 10911 located just below Kickapoo Cove (Figure 4-9A). Downstream, approximately 20 river miles from Station 10911, at Station 10899 (just upstream of the dam), Chl-a concentrations showed a slight decrease (Figure 4-9B). Higher Chl-a and pH values have been associated with warm season months since 1970 at all lake stations except for the uppermost station, 10917. This departure from Chl-a and pH seasonality at Station 10917 is notable because it contrasts with other Lake Livingston stations but is consistent with seasonal patterns and overall decreases in values in the Trinity River.

Table 4-4 Direction and significance of long-term trends, 1970 – 2011, in Lake Livingston (Segment 0803). Non-significant trends indicated by "NS"; significant ("*"; $p \leq 0.05$) and strongly significant ("*"; $p \leq 0.001$) trends are highlighted yellow and orange, respectively; nd = no data.

	Lake Livingston	*(stations listed in upstream to downstream order from left to right)*										
	10917		10914		10913		10909		10911		10899	
Parameter	n	Trend/Sig	n	Trend/Sig	n	Trend/Sig	n	Trend/Sig	n	Trend/Sig	n	Trend/Sig
NH_3	450	- / **	472	- / **	191	- / **	149	- / **	201	- / **	410	- / **
TKN	327	- / **	360	- / **	155	- / **	120	- / **	166	- / *	342	- / **
NO_3	242	+ / *	265	+ / **	145	+ / NS	125	- / NS	154	+ / NS	236	+ / *
NO_{23}	121	+ / NS	143	+ / NS	44	+ / NS	42	+ / NS	44	- / NS	98	+ / NS
OP	421	- / **	443	- / **	185	- / **	149	- / *	193	- / **	394	- / **
TP	409	- / **	415	- / **	180	- / **	142	+ / NS	191	- / *	366	- / **
Chl-a	293	- / NS	339	+ / NS	165	+ / *	142	+ / *	180	+ / **	322	- / NS
SO_4	427	- / NS	457	+ / NS	169	+ / *	122	+ / NS	183	+ / **	356	+ / **
E. coli	101	- / NS	98	- / NS	27	- / NS	25	- / NS	25	- / NS	57	+ / NS
TSS	450	+ / NS	449	+ / NS	189	+ / *	154	+ / NS	203	+ / NS	407	+ / **
BOD_5	67	- / *	113	+ / NS	61	+ / NS	52	+ / NS	72	+ / **	113	+ / *
Fcoli	239	- / NS	234	+ / NS	119	+ / NS	99	+ / NS	126	- / NS	265	+ / NS
pH	472	+ / **	504	+ / *	194	+ / *	154	+ / *	228	+ / **	417	+ / *
Alk	445	- / **	448	- / NS	193	- / NS	156	+ / NS	196	- / NS	414	- / **
WaterT	479	+ / NS	526	+ / NS	196	+ / *	156	+ / *	233	+ / *	434	+ / NS

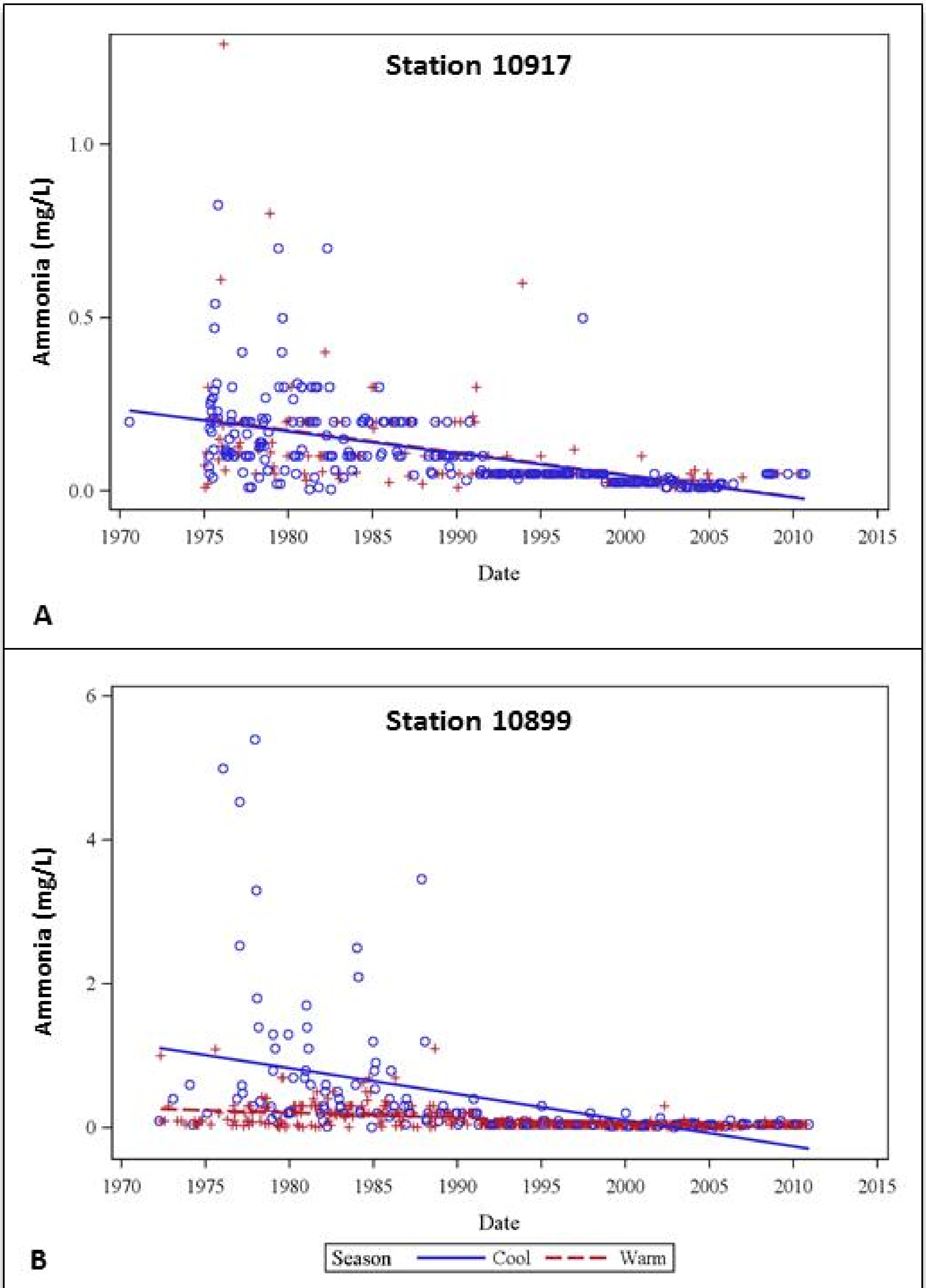

Figure 4-7 Temporal trends by season in NH_3, 1970 – 2011, Stations 10917 (A) and 10899 (B).

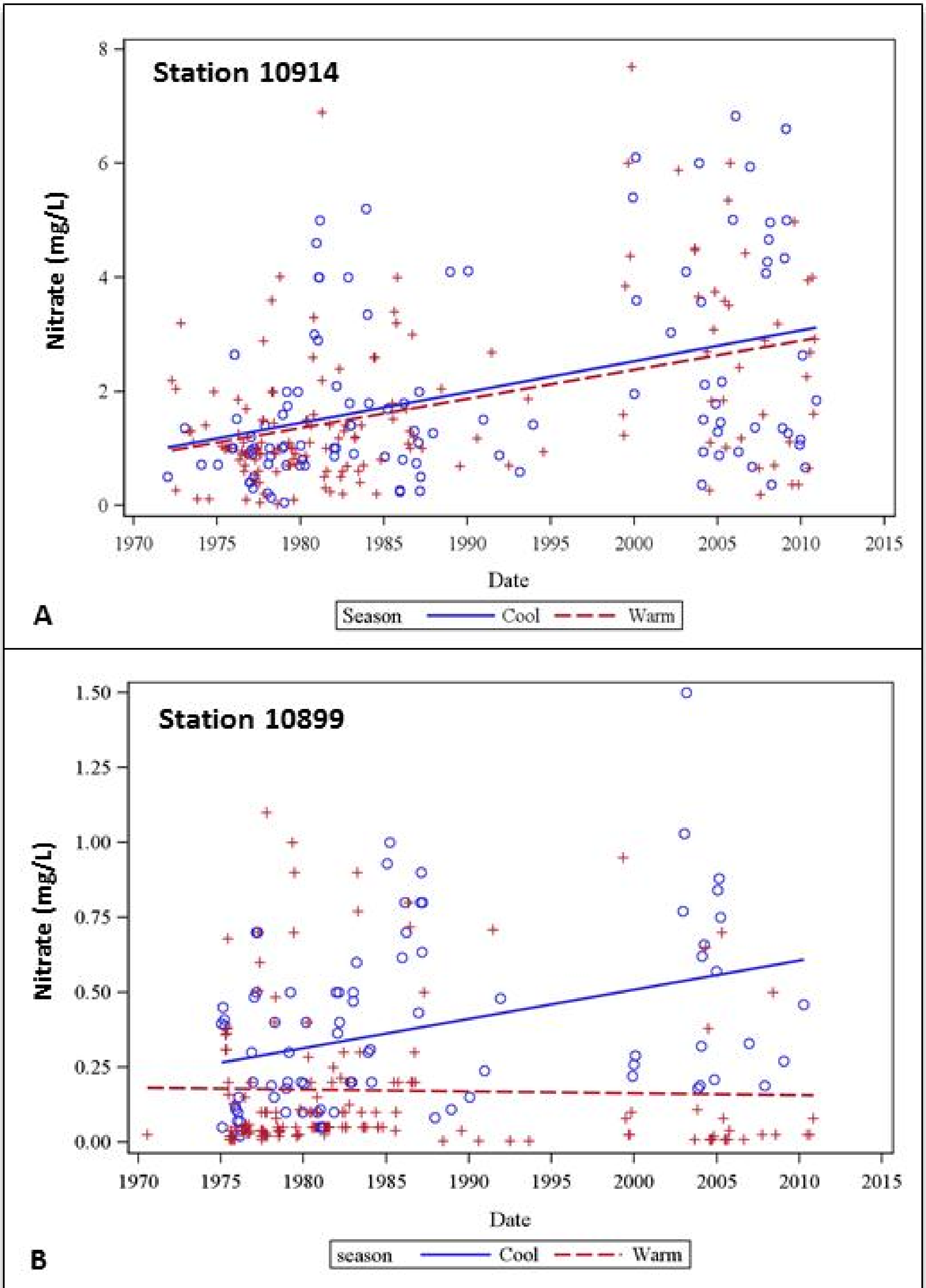

Figure 4-8 Temporal trends by season in NO_3, 1970 – 2011, Stations 10914 (A; AU 0803_10) and 10899 (B; AU 0803_01).

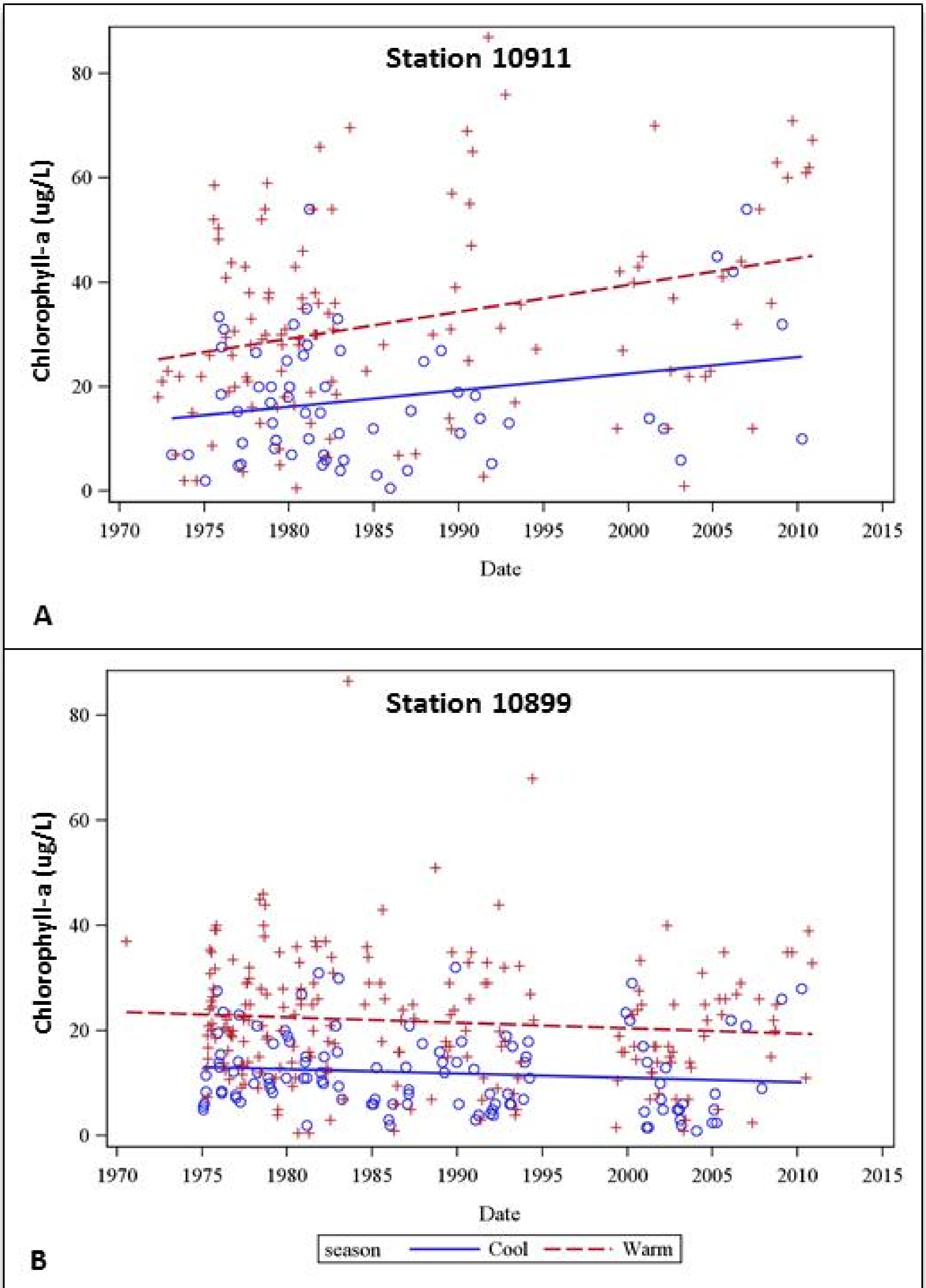

Figure 4-9 Temporal trends by season in Chl-a, 1970 – 2011, Stations 10911 (A) and 10899 (B).

Spatial and Temporal Water Quality Trends Since 1991

Trinity River Stations

The same river stations as for the long-term trend analyses were evaluated for a reduced, more recent dataset. Temporal trends were weaker for the recent 21 years, 1991 – 2011, than for the entire 42-year dataset. Strongly significant increases in NO_{23} and SO_4 occurred at Station 10925 (AU 0805_02), pH at Station 10919 (AU 0804_04) and SO_4 and Fcoli at Station 10918/13690 (AU 0804_01; Table 4-5). The upward trend in Fcoli is only slight and must be interpreted in the context of *E. coli*, which replaced Fcoli as a measure of bacteria in the Trinity River in 2002. In the last 10 years *E. coli* has shown an insignificant decrease at the same station. Overall, bacteria counts in the Trinity River are primarily a problem in the upper reaches where samples exceed the geometric mean criteria of 126 colonies/100 mL with some regularity (Figure 4-10).

Based on relatively sparse data, NO_3 did not show a significant increase over time except at Station 10925 and stations downstream of 10925 actually showed an insignificant decrease (Table 4-5). Spatially, all selected stations with NO_3 data had values well above the screening level of 1.95 mg/L. A more robust dataset existed for NO_{23}. In contrast to the NO_3 data, NO_{23} trends were upward, though the only significant trend was at Station 10925 (Figure 4-11; Table 4-5). NO_{23} levels were relatively high through Segment 0805 and begin to steadily decline from Station 10921/10922 (AU 0804_07) to the last station above Lake Livingston, 10918/13690 (AU 0804_01). Because of the greater number of data, upward temporal trends in NO_{23} are more likely indicative of what is actually occurring in the Trinity River than the downward trends for NO_3.

The only constituent with a significant trend at all stations was pH. At Station 10919 pH rose considerably over the past 20 years. In the early 1990s, pH hovered around 7.5 but more recently consistently reads around 7.8 (Figure 4-12A). The pH increase was small at 10918/13690 and is associated almost entirely with warm-season samples (Figure 4-12B). Although the median values at 10918/13690 were not significantly different from stations upstream, high-end and low-end values were more extreme and more frequently fell outside the pH criteria set by the TCEQ (Figure 4-13).

The drop in significance of trends between the 40-year and 20-year datasets is almost certainly partly attributable to the advanced treatment processes implemented in the DFW area and the phosphorus ban in detergents; both occurring by the early 1990s. Indeed, the decision to use 1990-1991 to demarcate “historical” and “recent” datasets was based, in part, on the need to distinguish nutrient water quality before and after the full implementation of these two events so their effects would not confound statistical analysis of data more typical of modern conditions.

Table 4-5 Direction and significance of recent trends, 1991 – 2011, in the Trinity River (Segments 0804 & 0805). Non-significant trends indicated by "NS"; significant ("*"; $p \leq 0.05$) and strongly significant ("*"; $p \leq 0.001$) trends are highlighted yellow and orange, respectively; nd = no data.

	Trinity River ***(stations listed in upstream to downstream order from left to right)***									
	10934		**10925**		**10921 & 10922**		**10919**		**10918 & 13690**	
Parameter	*n*	Trend/Sig	*n*	Trend/Sig	*n*	Trend/Sig	*n*	Trend/Sig	*n*	Trend/Sig
NH_3	251	- / NS	198	- / NS	126	- / NS	141	- / *	314	- / *
TKN	207	+ / NS	105	+ / *	110	+ / *	116	- / *	194	+ / NS
NO_3	78	+ / NS	51	+ / *	1	nd	16	- / NS	96	- / NS
NO_{23}	258	+ / NS	200	**+ / ****	124	+ / NS	139	+ / NS	211	+ / NS
OP	255	- / *	197	- / NS	126	- / NS	140	- / NS	307	- / NS
TP	248	- / *	125	- / NS	125	+ / NS	125	- / NS	200	- / NS
Chl-a	107	+ / *	111	+ / *	98	+ / NS	126	+ / *	139	+ / NS
SO_4	187	+ / NS	140	**+ / ****	63	+ / NS	82	+ / *	311	**+ / ****
E. coli	111	+ / NS	114	- / NS	95	+ / NS	86	+ / NS	101	- / NS
TSS	17	+ / NS	25	+ / NS	26	- / NS	73	- / NS	228	- / NS
BOD_5	17	+ / NS	89	- / NS	20	+ / NS	nd	nd	92	**+ / ****
Fcoli	12	+ / NS	17	- / NS	14	+ / NS	51	- / NS	88	+ / NS
pH	329	+ / *	226	+ / *	132	+ / *	147	**+ / ****	348	+ / *
Alk	14	- / NS	19	- / NS	21	- / NS	57	- / NS	243	- / NS
WaterT	331	+ / NS	227	+ / NS	133	+ / NS	152	+ / NS	355	+ / NS

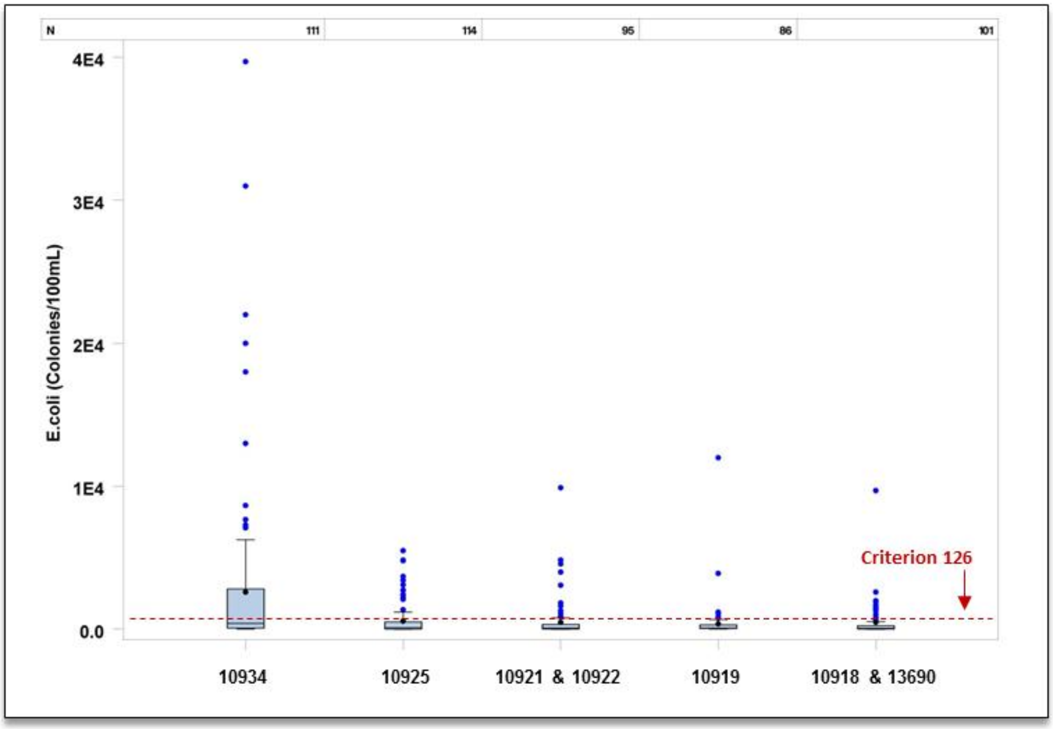

Figure 4-10 Spatial trends in *E. coli*, 1991-2011, Trinity River (Segments 0805 & 0804); stations are ordered upstream to downstream.

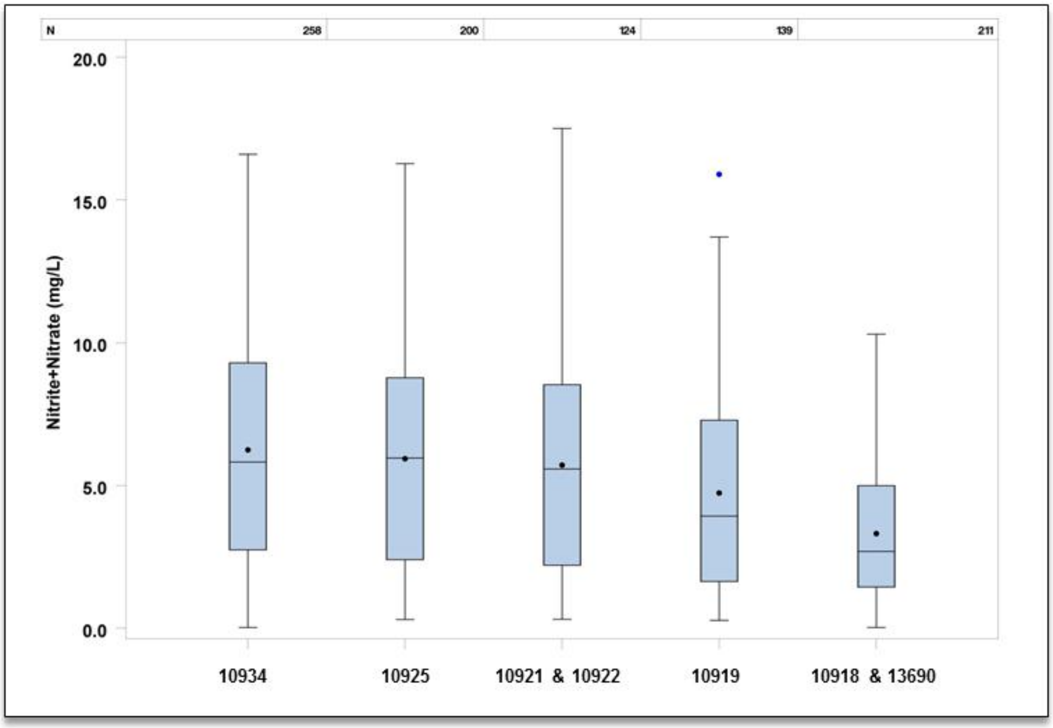

Figure 4-11 Spatial trends in NO_{23}, 1991-2011, Trinity River (Segments 0805 & 0804); stations are ordered upstream to downstream.

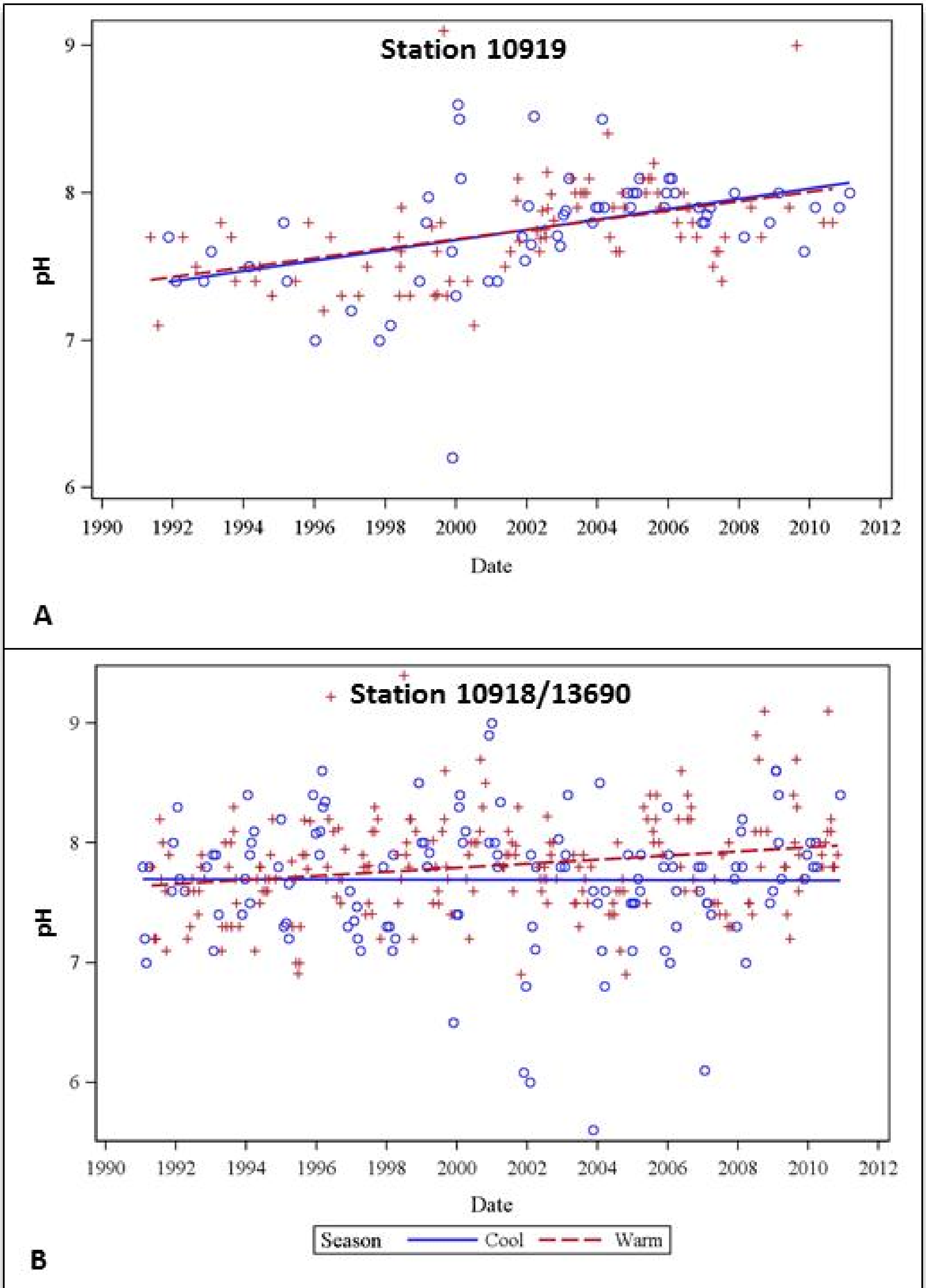

Figure 4-12 Temporal trends in pH, 1991-2011, Stations 10918/13690 (AU 0804_01) and 10919 (AU 0804_04).

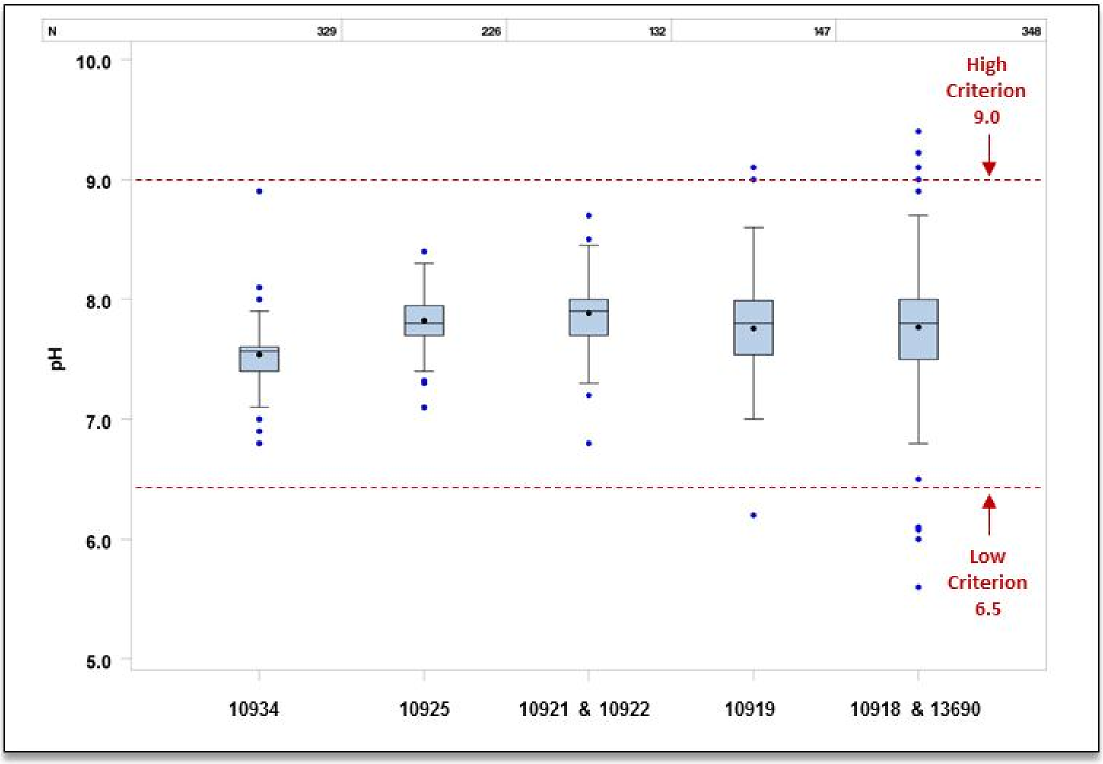

Figure 4-13 Spatial trends of pH, 1991 – 2011, for Trinity River stations (Segments 0804 & 0805); stations are ordered upstream to downstream.

Tributary Stations

Trends for the same set of tributary stations used in the long-term trend analyses were generally insignificant except at Tehuacana Creek (Station 10705), where the pH actually dropped (Table 4-6; Figure 4-14), contrary to upward trends in pH at almost all other stations whether Trinity River, Lake Livingston or on tributaries. Minimum values of pH on Tehuacana Creek have not yet dropped below the minimum criterion of 6.5 for pH, but should this decreasing trend in pH continue, occasional excursions are likely in coming years. NH_3 has also dropped slightly in Tehuacana Creek since 1991 and in the most recent 10 years most NH_3 concentrations have been near the limit of detection, ranging 0.01 – 0.05 mg/L.

Nutrient concentrations for Harmon Creek were significantly higher than for other tributaries and exceeded applicable screening levels (Figure 4-15). The number of samples were small for NO_3 (eight samples between 2003 and 2010), but half of these samples were taken in cool months and half in warm months and values from both seasons far exceeded the freshwater stream screening level of 1.95 mg/L for NO_3 (Figure 4-16A). Samples were more abundant for OP (n = 32) and TP (n = 30), and both phosphorus parameters exhibited year-around levels in exceedance of their respective screening levels (Figure 4-16B & C). The largest permitted discharge in Segment 0803 is the City of Huntsville WWTF, which discharges into Harmon Creek via Parker Creek and is a likely source of these higher nutrient concentrations.

Table 4-6 Direction and significance of recent trends, 1991 – 2011, in select tributaries of Lake Livingston. Non-significant trends indicated by "NS"; significant ("*"; $p \leq 0.05$) and strongly significant ("*"; $p \leq 0.001$) trends are highlighted yellow and orange, respectively; nd = no data.

	Tributaries							
	10717 Catfish Cr.		**10705 Tehuacana Cr.**		**10702 & 10703 Bedias Cr.**		**10698 Harmon Cr.**	
Parameter	n	Trend/Sig	n	Trend/Sig	n	Trend/Sig	n	Trend/Sig
NH_3	39	- / NS	93	**- / ** **	45	- / NS	38	+ / NS
TKN	33	- / *	14	- / NS	30	+ / NS	14	+ / NS
NO_3	17	- / NS	14	+ / NS	6	- / NS	8	- / NS
NO_{23}	38	- / NS	92	+ / NS	40	- / NS	14	+ / NS
OP	38	- / *	93	- / NS	45	+ / NS	32	- / NS
TP	41	- / NS	14	- / NS	42	+ / *	30	- / *
Chl-a	37	+ / NS	nd	nd	11	+ / NS	20	- / NS
SO_4	42	+ / NS	94	- / NS	44	+ / NS	37	+ / NS
E. coli	29	- / NS	nd	nd	11	+ / NS	15	+ / NS
TSS	41	+ / NS	92	- / NS	17	- / NS	38	- / NS
BOD_5	nd	nd	90	+ / NS	nd	nd	nd	nd
Fcoli	8	+ / NS	nd	nd	7	- / NS	17	- / NS
pH	43	+ / NS	107	**- / ** **	46	+ / *	40	+ / *
Alk	40	- / NS	nd	nd	22	- / NS	39	- / *
WaterT	43	- / NS	108	+ / NS	49	+ / NS	40	+ / NS

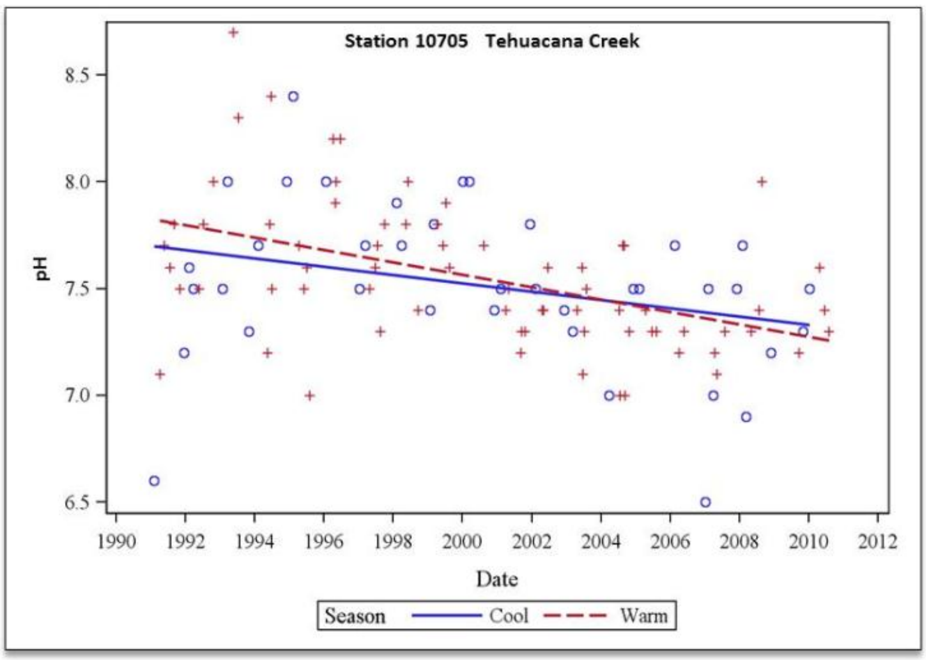

Figure 4-14 Temporal trends by season in pH, 1991 – 2011, Tehuacana Creek (Station 10705).

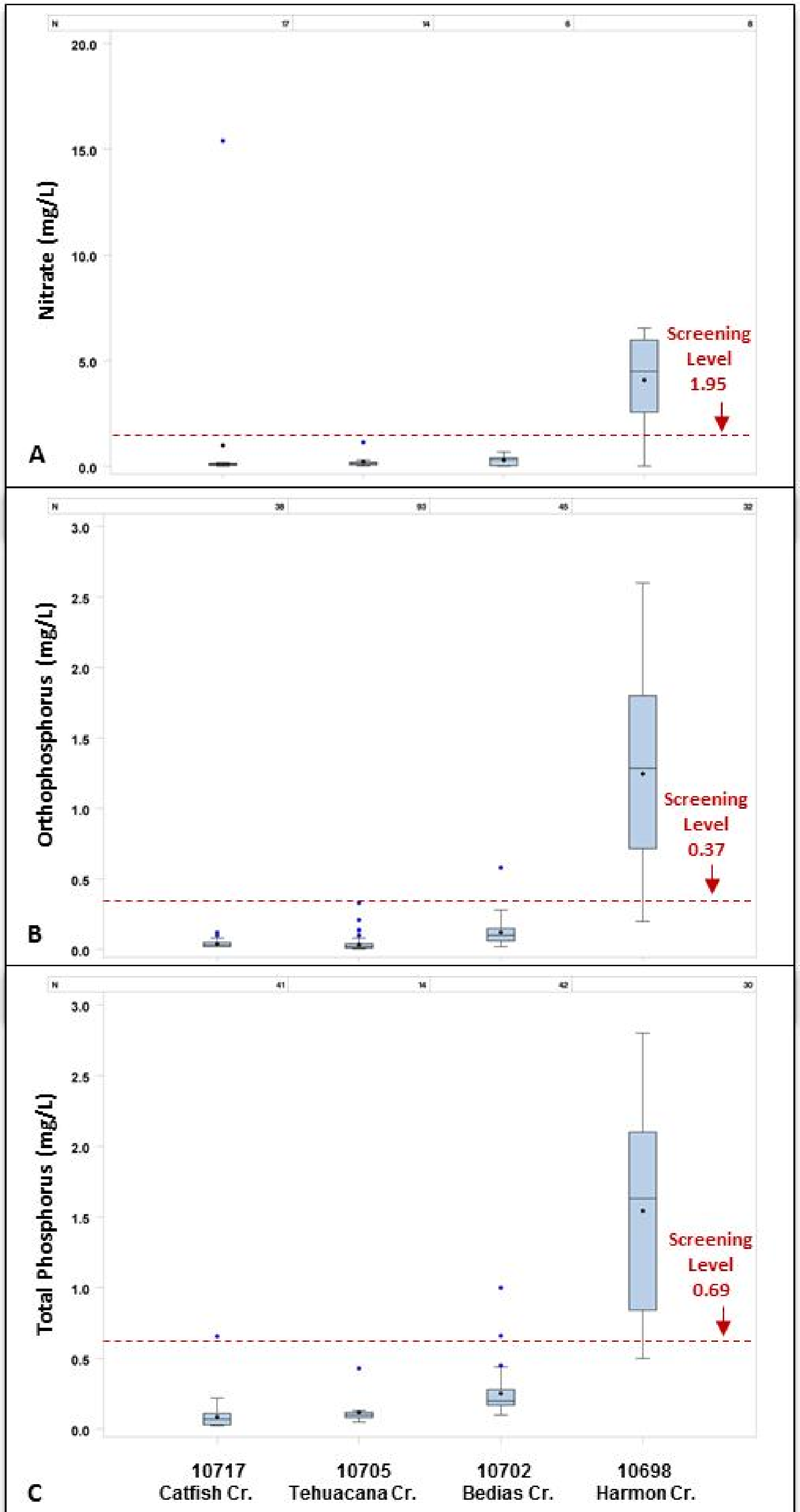

Figure 4-15 Spatial trends of NO_3 (A), OP (B) and TP (C), 1991 – 2011, for select tributaries of Lake Livingston.

Lake Livingston Stations

For the same lake stations used in the long-term trend analyses, the only constituents that demonstrated a significant lake-wide trend since 1991 were NH_3 (negative) and SO_4 (positive; Table 4-7). The most significant downward pattern for NH_3 occurred at Station 10899, above the dam (Figure 4-16). However, this trend was strongly influenced by high NH_3 concentrations (0.1 – 0.6 mg/L) occurring between 1991 and 2001, and those high NH_3 concentrations occurred mostly with cool-season samples. Since that time, values have ranged well below the screening level of 0.11 mg/L. The same negative trend patterns in NH_3 at Station 10899 held true for Stations 10917 and 10914 in the upper lake, Station 10909 in Kickapoo Cove and Trinity River stations above Lake Livingston (Table 4-5). The sharpest increases in SO_4 were associated with cool-season samples in the upper lake at Stations 10917, 10914 and 10913 (see Figure 4-17 for Station 10917). As with NH_3, concentrations of SO_4 dropped with distance downstream across the reservoir (Figure 4-18).

Table 4-7 Direction and significance of recent trends, 1991 – 2011, in Lake Livingston (Segment 0803). Non-significant trends indicated by "NS"; significant ("*"; $p \leq 0.05$) and strongly significant ("*"; $p \leq 0.001$) trends are highlighted yellow and orange, respectively; nd = no data.

	Lake Livingston (stations listed in upstream to downstream order from left to right)											
	10917		**10914**		**10913**		**10909**		**10911**		**10899**	
Parameter	*N*	Trend/Sig	*n*	Trend/Sig	*n*	Trend/Sig	*n*	Trend/Sig	*n*	Trend/Sig	*n*	Trend/Sig
NH_3	221	- / *	244	- / *	52	- / NS	43	- / *	52	- / NS	180	**- / ****
TKN	178	- / NS	176	+ / NS	46	+ / NS	41	+ / NS	49	+ / NS	138	**+ / ****
NO_3	68	- / NS	87	- / NS	26	+ / NS	25	- / NS	26	- / NS	50	- / NS
NO_{23}	118	+ / NS	138	+ / NS	40	+ / NS	40	- / NS	40	- / NS	94	- / NS
OP	208	- / NS	229	+ / NS	49	- / NS	43	- / NS	50	- / NS	167	- / NS
TP	187	- / NS	189	+ / NS	42	- / NS	34	- / NS	42	+ / NS	140	- / NS
Chl-a	142	+ / *	157	+ / NS	39	+ / NS	39	+ / *	44	+ / NS	118	+ / NS
SO_4	215	+ / *	243	**+ / ****	53	+ / *	44	+ / NS	53	+ / NS	183	+ / *
E. coli	101	- / NS	98	- / NS	27	- / NS	25	- / NS	25	- / NS	57	+ / NS
TSS	225	- / NS	226	- / NS	54	- / NS	47	- / NS	55	- / NS	180	**- / ****
BOD_5	Nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Fcoli	87	+ / NS	93	+ / NS	27	- / NS	23	+ / NS	27	- / NS	118	- / NS
pH	232	+ / NS	257	+ / NS	56	- / NS	48	+ / NS	65	+ / NS	189	+ / NS
Alk	225	- / NS	230	- / NS	56	- / NS	48	+ / NS	56	- / NS	185	- / NS
WaterT	235	+ / NS	258	+ / NS	56	+ / NS	48	+ / NS	66	+ / NS	200	+ / *

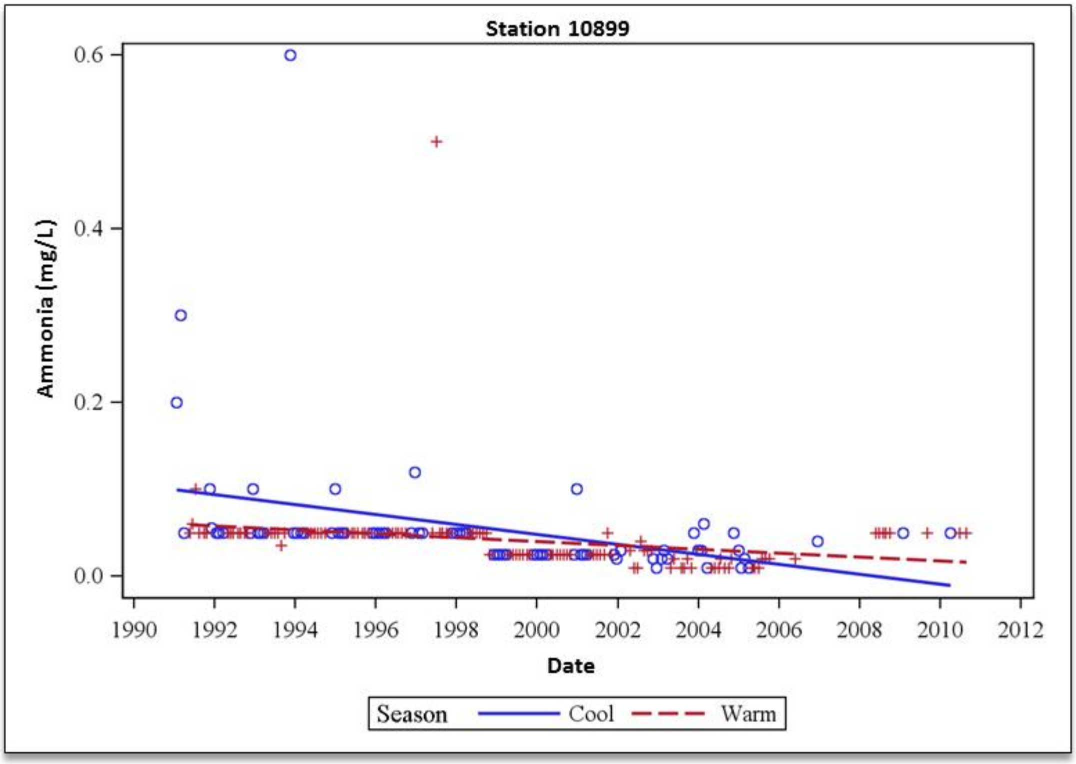

Figure 4-16 Temporal trends by season in NH_3, 1991 – 2011, Station 10899 (0803_01).

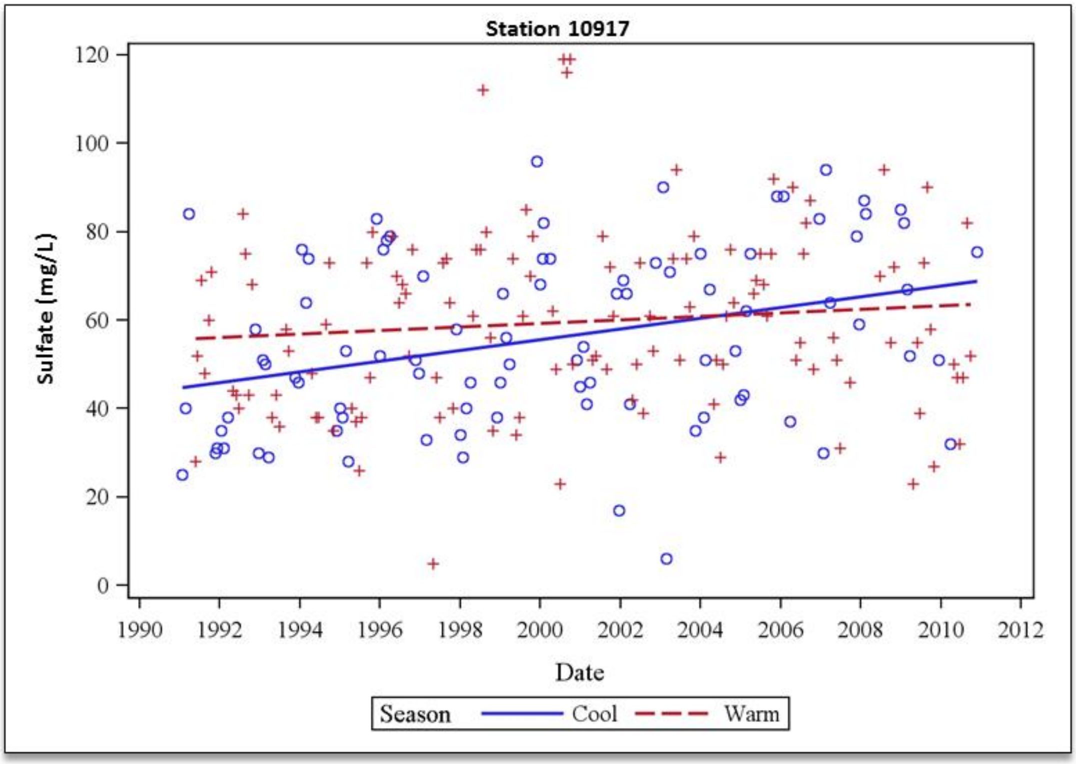

Figure 4-17 Temporal trends by season in SO_4, 1991 – 2011, Station 10917 (0803_11).

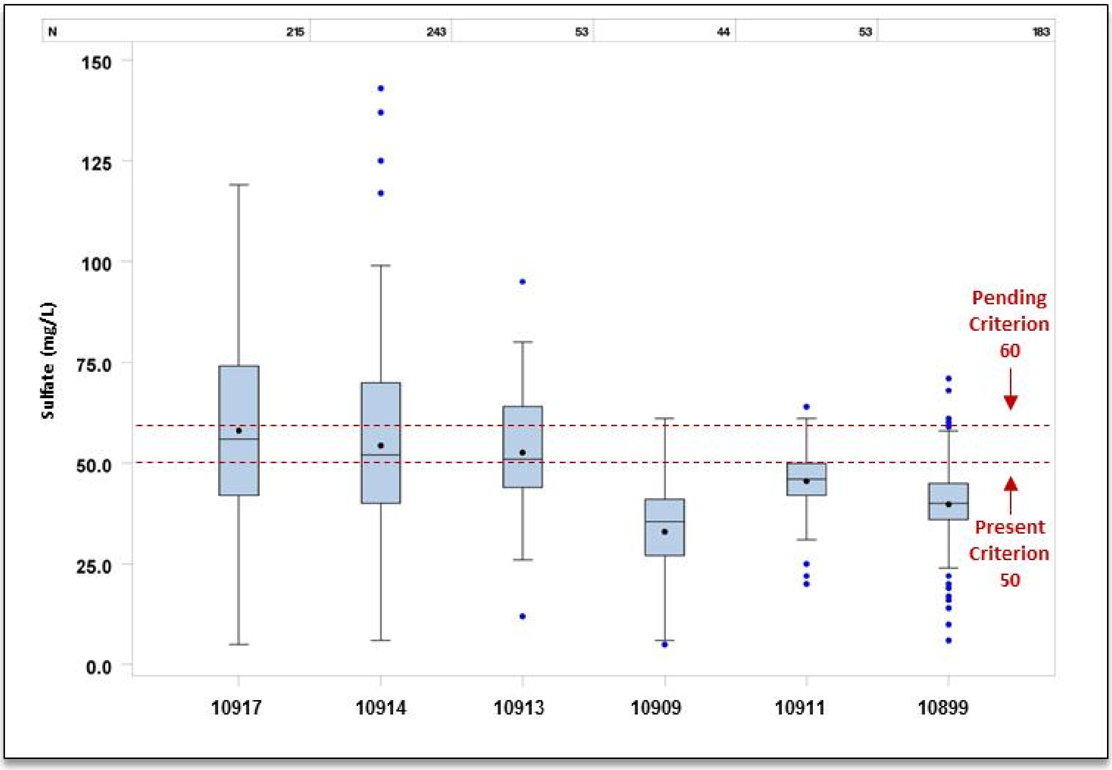

Figure 4-18 Spatial trends in SO_4, 1991 – 2011, in Lake Livingston (Segment 0803); stations are ordered upstream to downstream across the reservoir.

Spatial and Intra-annual Temporal Variability in Water Quality Conditions

Lake Livingston has been on CWA Section 303(d) lists for high pH since 2008 and SO_4 since 2010. In addition, NO_3, TP and Chl-a regularly exhibited values above their respective screening levels. Tables 4-8 – 4-13 display both spatial and intra-annual (monthly) patterns of selected parameters covering 1991 – 2010 from monitoring of the near-surface water. The values in each cell represent the 75th percentile and deeper shades of color represent higher values. The 75th percentile for each water quality parameter was selected for these tables as a "reasonable" high value that if exceeding relevant criteria or screening levels could be an indication of water issues regarding that parameter. The information in these tables is not intended for strict CWA assessment purposes, but rather for general discussions of Lake Livingston conditions within the context of findings from the 2010 TCEQ Integrated Report (TCEQ, 2010b). Mathematically, the 75th percentile value is the value below which 75 percent of the data values occur and conversely above which 25 percent of the data values occur.

Table 4-8 Water temperature (°C) 75th percentile by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Water Temperature (°C) 75th Percentile	10917	Upper Lake	12.4	15.0	19.9	23.2	27.0	30.1	31.5	32.0	27.0	22.0	16.5	12.6
	10914		13.7	15.3	20.1	23.0	30.0	31.6	33.0	33.2	29.9	23.7	18.3	12.5
	10913		14.0	24.0	20.3	25.1	28.2	31.3	32.4	33.9	28.1	25.4		12.9
	14013		10.0*	14.5	14.0*					32.0	32.5*			
	14010	Mid Lake	11.0*	14.5	13.0*					32.0	32.0*			
	10911		13.8	15.0	21.0	23.9	28.0	32.6	31.6	32.6	28.4	25.8		13.5
	14008		11.0*	14.5	12.5*					30.7	30.0*			
	14007		11.0*	14.0	12.5*					30.9	30.8*	23.2*	16.5*	
	14006	Lower Lake	12.0*	13.5	12.0*					31.0	30.1*	23.4*	18.0*	
	14005		12.0*	14.0	12.0*					30.8	30.0*	24.3*	17.6*	
	10899		12.8	14.3	18.0	23.1	26.9	30.8	31.8	31.9	28.8	24.1	19.2	14.1
	14003	Dam	11.5*	14.0	12.0*					31.3	30.5*			
	10909	Kickapoo Cove	16.2	11.7*	20.5	25.2	31.0	34.0	34.1	32.7	31.0	28.2*		14.8
	14009		10.0*	14.5	12.5*					30.9	30.0*			
	14014	White Rock Cove	9.5*	15.5	14.5*					33.0	32.5*	23.6*	16.1*	

Table 4-9 pH (standard units) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
pH 75th Percentile	10917	Upper Lake	8.3	8.1	8.0	8.0	8.0	8.1	8.4	8.3	8.1	8.2	8.0	8.0
	10914		8.0	7.9	8.1	8.0	8.4	8.8	8.8	8.9	8.5	8.2	7.9	8.1
	10913		8.3	7.6	7.7	8.3	8.7	8.6	9.0	9.1	8.5	8.7		8.1
	14013		8.1*	8.3	8.2*					9.2	9.5*			
	14010	Mid Lake	8.0*	8.0	8.2*					9.1	9.5*			
	10911		8.2	7.9	8.1	8.3	8.9	9.2	9.1	9.0	9.4	8.5		8.6
	14008		7.9*	8.1	8.2*					8.9	8.8*			
	14007		7.9*	8.1	8.1*					8.9	8.9*	8.5*	8.4*	
	14006	Lower Lake	7.9*	8.1	8.1*					8.8	9.0*	8.3*	8.3*	
	14005		7.9*	8.1	8.0*					8.8	8.9*	8.6*	8.2*	
	10899		8.3	8.0	8.2	8.6	9.0	9.0	9.0	9.0	8.7	8.5	8.1	8.1
	14003	Dam	7.9*	8.0	8.1*					8.9	8.8*			
	10909	Kickapoo Cove	8.6	8.4*	8.7	8.0	9.2	9.0	9.1	8.9	8.6	8.7*		8.4
	14009		7.8*	8.3	8.1*					9.0	8.7*			
	14014	White Rock Cove	7.7*	8.1	8.3*					9.0	9.6*	8.1*	8.5*	

Table 4-10 Sulfate (mg/L) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Sulfate (mg/L) 75th Percentile	10917	Upper Lake	76.0	67.0	74.0	66.0	55.0	64.0	81.5	82.0	72.0	76.0	75.5	59.0
	10914		76.0	72.0	61.0	60.0	71.0	58.5	78.0	78.8	73.0	77.0	70.0	54.0
	10913		66.0	46.0*	45.0	57.0	60.0	66.0	51.0	80.0	50.0	95.0		69.0
	14013		50.0*	41.0	56.0*					57.1	55.8*			
	14010	Mid Lake												
	10911		54.0	46.0*	44.0	57.0	64.0	50.0	51.0	49.0	50.0	58.0*		47.0
	14008									39.0*	34.0*			
	14007													
	14006	Lower Lake												
	14005													
	10899		45.0	47.5	42.0	43.0	47.5	43.0	41.0	44.0	42.5	47.5	47.0	47.0
	14003	Dam	29.6*	40.3	33.6*					39.2	33.8*			
	10909	Kickapoo Cove	45.0	18.0*	38.0	46.0	61.0*	45.0	37.0	39.0	40.0	32.0*		40.0
	14009													
	14014	White Rock Cove												

Table 4-11 Nitrate (mg/L) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Nitrate (mg/L) 75th Percentile	10917	Upper Lake	4.49	5.24	2.46	3.03	3.20	1.18	5.90	5.10	5.46	6.82	6.78	4.49
	10914		6.10	4.97	2.15	2.42	3.59	1.85	3.19	5.36	3.73	6.00	5.01	4.31
	10913		5.00*	0.73*	1.41*	2.58*	0.67*	0.97	1.57	0.80	1.23*	0.69*		3.70
	14013		1.48*	0.92*	1.50*					1.24				
	14010	Mid Lake												
	10911		1.79*	0.37*	0.89*	1.00*	0.57*	0.86	0.44	0.03	0.28*	0.93*		0.79
	14008			0.61*						0.10*				
	14007													
	14006	Lower Lake												
	14005													
	10899		0.84	1.50	0.75	0.95	0.50*	0.38	0.03	0.03	0.03	0.10	0.22	0.57
	14003	Dam		2.88*										
	10909	Kickapoo Cove	0.38*	0.27*	0.06*	0.09*	0.03*	0.17	0.02	0.03	0.03*	0.01*		0.24
	14009		0.99*	0.84*										
	14014	White Rock Cove	0.65*	0.29*	0.89*					1.44				

Table 4-12 Total phosphorus (mg/L) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Total Phosphorus (mg/L) 75th Percentile	10917	Upper Lake	0.95	0.80	0.59	0.57	0.60	0.77	0.71	0.89	0.87	1.10	0.97	0.90
	10914		0.55	0.51	0.53	0.36	0.40	0.60	0.39	0.80	0.52	0.75	0.80	0.66
	10913		0.53	0.41*	0.40	0.65	0.30	0.26	0.32	0.29	0.40	0.36		0.53
	14013													
	14010	Mid Lake												
	10911		0.33	0.36*	0.20	0.24	0.18	0.21	0.20	0.50	0.30	0.20*		0.24
	14008													
	14007													
	14006	Lower Lake												
	14005													
	10899		0.20	0.20	0.20	0.16	0.20	0.14	0.12	0.17	0.20	0.14	0.20	0.20
	14003	Dam												
	10909	Kickapoo Cove	0.24	0.18*	0.50	0.18	0.18	0.19	0.60	0.24	0.18*	0.22*		0.17
	14009													
	14014	White Rock Cove												

Table 4-13 Chlorophyll-a (µg/L) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Chlorophyll-a (µg/L) 75th Percentile	10917	Upper Lake	35.0	15.0	12.0	6.0	15.0	10.0	16.0	18.0	10.0	15.0	21.0	13.0
	10914		19.0	19.0	17.0	13.0	16.0	25.4	44.0	43.0	28.9	24.0	10.0	11.0
	10913		40.0	2.5*	25.5	21.0	59.0	39.0	43.0	85.0	64.0	63.0		20.0*
	14013													
	14010	Mid Lake												
	10911		32.0	42.0*	29.5	17.0	60.0	42.0	43.0	62.0	81.5	67.3		54.0
	14008													
	14007													
	14006	Lower Lake												
	14005													
	10899		15.0	16.0	17.0	23.0	31.0	19.0	23.0	32.4	32.0	27.5	19.0	11.0
	14003	Dam												
	10909	Kickapoo Cove	30.5	13.0*	69.5	30.0	64.0	46.0	23.0	56.0	58.0*	27.6*		44.0*
	14009													
	14014	White Rock Cove												

For ecological context, monthly patterns in flow, dam releases and water temperature are presented in Table 4-8. The patterns in flow and releases are also repeated in each subsequent table for reference. A set of tables for 14 of the 15 key parameters is presented in Appendix A (BOD_5 data were lacking in Lake Livingston).

The information included in these tables is from two broad groupings of stations referred to as the 10000 series (stations 10899, 10909, 10911, 10913, 10914 and 10917) and the 14000 series (stations 14003, 14005, 14006, 14007, 14008, 14009, 14010, 14013 and 14014). The 10000-series stations are long-term stations with data going from the 1970s to the present, whereas the 14000-series stations were monitored most intensely over the period 1993 – 2005 with a few stations monitored for a couple more years. The 14000-series stations were typically monitored once in winter and in summer (typically February and August) and for a more limited suite of parameters than the 10000-series stations. The tables revealed major data gaps in 14000-series stations that were particularly glaring in the mid and lower lake and coves. However, 10000-series stations supplied sufficient information to decipher spatial and monthly patterns in the lake with some degree of confidence. Data in Kickapoo and White Rock Coves were sparse but were included to elucidate potential water quality concerns at locations peripheral to the main body of Lake Livingston. Some months and some parameters were better represented than others. Working with available data, the following summarizes the spatial and monthly patterns of selected parameters from 1991 – 2010:

- **Water temperatures** reflected the anticipated annual patterns similar to those experienced with air temperatures with lowest values in January and peak values in a July-August time frame (Table 4-8). Stratification increased through the late spring reaching a peak in July and August (Figure 2-12) when surface water temperatures were at their annual maximum. Decreasing surface water temperatures in early fall (September – October) coincided with mixing of the water column and reduced inflows and dam releases (Table 4-8).

- Summer was clearly the season for high **pH** in the lake, particularly in the mid and lower lake and Kickapoo cove (Table 4-9). The timing of high pH in Lake Livingston coincided with diminished inflows from the Trinity River (USGS 08065350) and Bedias Creek (USGS 08065800).

- **SO_4** was consistently above the criterion of 60 mg/L in the upper lake with the largest excursions occurring in July and August (Table 4-10). Values in the lower lake and Kickapoo Cove were not generally above the criterion but maintained moderately high values. SO_4 exhibited a clear inverse relationship to Trinity River flow in the upper lake, a pattern that was present but less distinct near the dam. While the SO_4 criterion is assessed by TCEQ as a long-term average for the entirety of Segment 0803 (not at the AU level of spatial refinement), this temporal and spatial analysis provides additional insights into the SO_4 levels in Lake Livingston.

- **NO_3** in Lake Livingston was highest in the upper lake with the highest values occurring August – February (Table 4-11). The only month where NO_3 was relatively low (though still several times greater than the screening level of 0.37 mg/L) was June. Limited data in Kickapoo Cove indicates NO_3 was not as high as in the upper half of the lake. A handful of samples in White Rock Cove showed high August concentrations consistent with the timing of high values in the upper portion of the lake.

- **TP** also far exceeded the screening level of 0.20 mg/L year around in the upper lake with concentrations consistently above 0.8 mg/L from August – February (Table 4-12). Station 10917, the most riverine water quality station in Lake Livingston, exhibited the highest concentrations when Trinity inflows were relatively diminished. In the lower lake, 75th percentile values hovered around the screening level of 0.20 mg/L throughout the year. The same can be said of Kickapoo Cove except in March and July when TP jumped to double the annual average of the cove.

- The 75th percentile of **Chl-a** exceeded the screening level of 26.7 µg/L in all sectors of the lake and not only in the summer peak growing season. Chl-a concentrations at Station 10899, located just above the dam, exceeded the proposed criterion of 22.96 µg/L primarily between April and October, during the warm season (Table 4-13). The highest concentrations occurred at Station 10911 in September and October, a location southwest of Kickapoo Cove, which also had the high pH readings. The timing of the Chl-a peak at Station 10911 coincided with high pH in September (Table 4-9) and followed an August – September spike in TP (Table 4-12) at the same station.

Following are notes on key parameters for which tables are located in Appendix A.

- **NH_3** sporadically exhibited concentrations in exceedance of the screening level of 0.11 mg/L, almost always during spring and early summer in mid-lake below Kickapoo Cove (Appendix A-1). Generally NH_3 stayed near the limit of detection.

- **TKN** maintained low to moderate levels throughout the lake but the upper lake had relatively higher values year around (Appendix A-2). The same range of 75th percentile values that existed in the lake, usually 0.7 – 1.4 mg/L, showed up in Kickapoo Cove.

- **NO_{23}** followed the patterns of NO_3, as expected, with very high concentrations throughout the year with peaks during July - January (Appendix A-4).

- **OP** in the upper lake was up to 10 times higher than the lower lake with 75th percentile values reaching 0.94 mg/L in October. The peak months for OP concentrations (July – January) paralleled peaks concentrations noted for NH_3, NO_3 and NO_{23} (Appendices A1, A3, and A4).

- ***E. coli*** data were quite scarce except in the upper lake where values exceeded the geometric mean criterion of 126 colonies/100 mL, primarily in the fall and winter months, with highest concentrations occurring in January and February at station 10917 (Appendix A-9).

- **TSS** was many times higher in the upper lake than the lower lake, sustaining levels above 200 mg/L much of the year (Appendix A-10). Peaks well over 300 mg/L occurred in

March, May and December. June – October were months with relatively low TSS in the mid lake region. This longitudinal pattern of decreasing TSS concentrations was anticipated given the relative quiescence of the lake, which provides opportunity for settling of particulates.

- **Fcoli** samples were collected from 1991 – 2002 and followed the pattern of the *E. coli* samples that replaced them with low to moderate concentrations year around with peaks in the fall and winter months (Appendix A-11). The upper lake samples were consistently higher than the lower lake by a factor of 10 for Fcoli.

- **Alky** ranged from 100 – 200 mg/L as $CaCO_3$ (Appendix A-13), which is more typical of central Texas reservoirs than east Texas where Lake Livingston is located. East Texas reservoirs generally have Alky values are considerably lower (15 – 76 mg/L as $CaCO_3$; Ground and Groeger, 1994). This perhaps points to the overarching influence of the hydrogeology of the Trinity River on Lake Livingston.

Patterns of Response in Lake Livingston Water Quality

Flow and Temperature as Forcing Factors

The temporal patterns of pH, SO_4, *E. coli*, Chl-a, NH_3, NO_3, OP and TP were given special attention, because these water quality parameters are associated with criteria and screening levels established by the TCEQ. Seasonality was noted in a few of these parameters, such as pH (Table 4-9), but other parameters seem to follow more closely the flow regime of the Trinity River. Cluster analysis is a useful tool for grouping “like” observations. In the following analyses, the Euclidian distance between monthly means of select parameters was used to group similar months together. These groups, or “clusters,” were further grouped in hierarchical fashion; the smaller the cluster height, the more similar the observations. The Lake Livingston data used for these analyses were from the 10000-series and 14000-series stations for the period of 1993 – 2005.

Cluster analysis of water temperature on Lake Livingston and flow at USGS 08065350 (Trinity River near Crockett) produced distinct seasonal patterns (Figures 4-19 & 4-20).[1] Within the primary water temperature clusters of warm and cool seasons, secondary clusters grouped according to deep summer (July – August), deep winter (December – January), warm-transitional (April and October) and cool-transitional (March and November). Flow also broke into two distinct seasons with high flows in November – June and low flows in July – October (Figure 4-20B). The cluster analysis correctly identified the peak flow period (February – March) and low flow period (August – September). Flow seasonality can be distinguished from temperature seasonality by a later, more distinct, “summer” that begins in July and hits the annual minimum in August - September. Temperatures, however, began their steepest incline in April with a peak

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[1] For these analyses water temperature and flow were considered causative factors that have the potential of soliciting a response in certain water quality parameters; a “cause and effect” relationship. It is realized that these two factors are in turn responses to larger factors such as the tilt of the earth on its axis, the earth’s geomorphology (topography, position of its major oceans and land masses) and the orbit of the earth about the sun, which drive large-scale patterns of climate causing the water temperature and flow patterns observed in Lake Livingston and its watershed.

in July. In summary, both flow and temperature exhibited seasonal patterns, but their phases were shifted such that flow minimums followed temperature maximums by approximately one month.

Seasonal clusters and boxplots of water temperature and flow were compared to determine whether the parameters are primarily *thermal-responsive*, *flow-responsive* or follow patterns that do not fit neatly into either of these seasonal patterns. Regressions of these parameters versus flow and water temperature also help elucidate strength and direction of the response to thermal and flow parameters (Table 4-14).

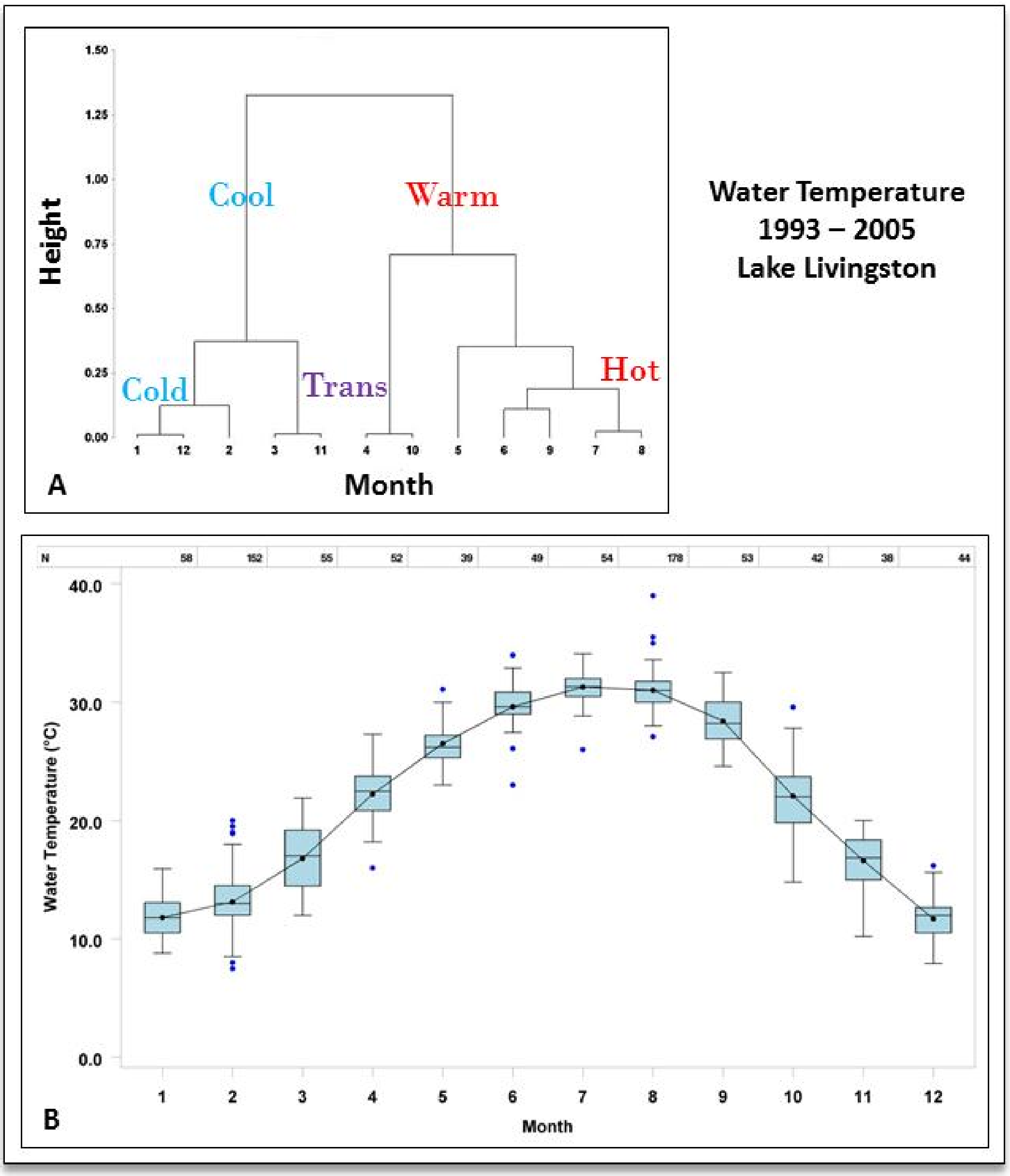

Figure 4-19 Cluster analysis of monthly means of surface water temperature at primary Lake Livingston stations (A) and boxplot by month (B). Data from 1993 – 2005.

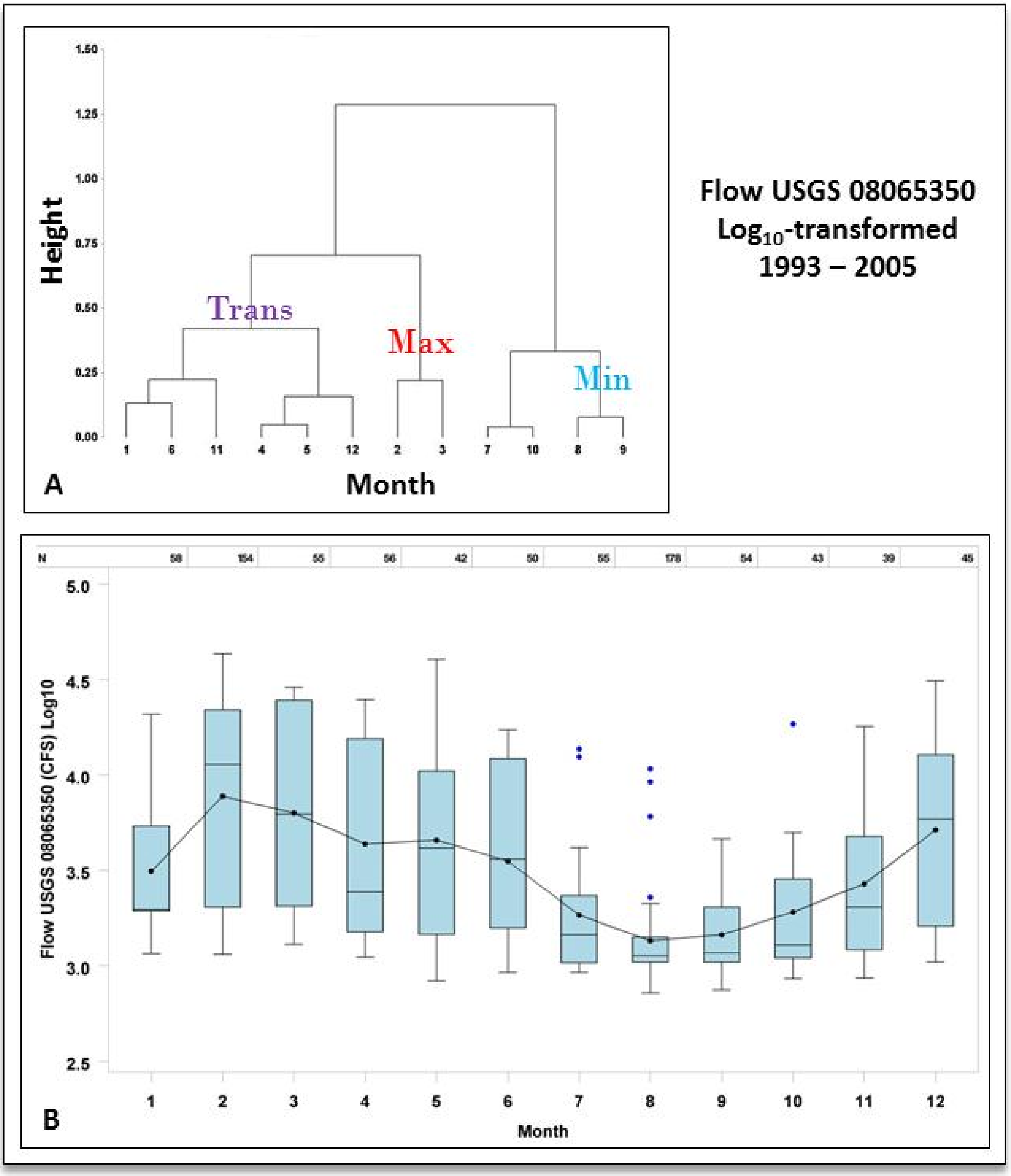

Figure 4-20 Cluster analysis of monthly means of log10-transformed flow at USGS 08065350 (A) and boxplot by month (B) for dates with water quality data at primary Livingston stations. Data from 1993 – 2005.

Table 4-14 Regressions of key parameters in Lake Livingston, 1993 – 2005; all values log10-transformed before evaluation except pH and WaterT. R^2 values ≥ 0.2 are highlighted as are *p*-values < 0.0001.

All Stations								
	USGS 08065350				**Water Temperature**			
	n	**R^2**	***p* ANOVA**	**Equation**	**n**	**R^2**	***p* ANOVA**	**Equation**
NH_3	644	0.0652	***< 0.0001***	y = -1.9734 + 0.1523x	633	0.0501	***< 0.0001***	y = -1.2591 - 0.0082x
TKN	385	0.0078	0.083	y = 0.0197 - 0.0338x	375	0.0002	0.7835	y = -0.1077 + 0.0003x
NO_3	149	0.0095	0.2364	y = -0.8277 + 0.2049x	148	0.0506	0.006	y = 0.3466 - 0.0218x
NO_{23}	406	0.0043	0.1897	y = -0.6197 + 0.1042x	400	0.0905	***< 0.0001***	y = 0.3638 - 0.0279x
OP	580	0.1049	***< 0.0001***	y = 0.0932 - 0.2838x	571	0	0.9644	y = -0.8953 - 0.0001x
TP	361	0.0047	0.1954	y = -0.3364 - 0.0542x	353	0.0148	0.0223	y = -0.3928 - 0.006x
CHLA	275	0.0893	***< 0.0001***	y = 2.0234 - 0.2821x	267	0.138	0.0005	y = 0.5246 + 0.0221x
SO_4	588	***0.213***	***< 0.0001***	y = 2.2805 - 0.1749x	577	0.0383	***< 0.0001***	y = 1.5623 + 0.0047x
Ecoli	158	0.1107	***< 0.0001***	y = -1.5914 + 0.8317x	152	0.1387	***< 0.0001***	y = 2.3626 - 0.0487x
TSS	500	0.1617	***< 0.0001***	y = -0.0137 + 0.4487x	493	0.0639	***< 0.0001***	y = 1.9512 - 0.0179x
Fcoli	321	0.0975	***< 0.0001***	y = 0.0934 + 04134x	315	0.1404	***< 0.0001***	y = 2.279 - 0.0334x
pH	803	***0.206***	***< 0.0001***	y = 10.054 - 0.5514x	799	***0.3119***	***< 0.0001***	y = 7.2149 + 0.0413x
Alk	523	0.0373	***< 0.0001***	y = 2.129 - 0.0361x	513	0.0782	***< 0.0001***	y = 1.9289 + 0.0033x
WaterT	814	***0.2349***	***< 0.0001***	y = 49.993 - 7.9692x	--	--	--	--
Upper Lake Livingston (Stations 10917 & 10914)								
	USGS 08065350				**Water Temperature**			
	n	**R^2**	***p* ANOVA**	**Equation**	**n**	**R^2**	***p* ANOVA**	**Equation**
NH_3	332	0.046	***< 0.0001***	y =-1.745 + 0.107x	325	0.0552	***< 0.0001***	y = -1.2005 - 0.0076x
TKN	227	0.004	0.3418	y = 0.0087 - 0.0227x	221	0.0063	0.2403	y = -0.0316 - 0.0018x
NO_3	69	***0.3339***	***< 0.0001***	y =2.0739 - 0.5026x	68	0.1021	0.0079	y = 0.0934 + 0.0133x
NO_{23}	179	***0.305***	***< 0.0001***	y = 1.9406 - 0.4847x	176	0.0218	0.0283	y = 0.079 + 0.0085x
OP	290	***0.4772***	***< 0.0001***	y = 1.309 - 0.5574x	284	0.0191	0.0197	y = -0.7948 + 0.0069x
TP	221	0.096	***< 0.0001***	y = 0.2709 - 0.1739x	216	0.0036	0.3789	y = -0.297 - 0.0022x
CHLA	154	0.0955	***< 0.0001***	y = 1.9444 -0.2853x	150	0.0481	0.007	y = 0.6493 + 0.0128x
SO_4	322	***0.4554***	***< 0.0001***	y = 2.6965 - 0.2786x	315	0.0669	***< 0.0001***	y = 1.565 + 0.0069x
Ecoli	91	***0.2696***	***< 0.0001***	y = -2.095 + 1.1045x	88	***0.2837***	***< 0.0001***	y = 3.0502 - 0.061x
TSS	293	***0.3675***	***< 0.0001***	y = -0.1152 + 0.5571x	289	0.1144	***< 0.0001***	y = 2.2774 - 0.0199x
Fcoli	177	***0.2315***	***< 0.0001***	y = -0.3655 + 0.6423x	174	***0.2362***	***< 0.0001***	y = 2.8219 - 0.0435x
pH	331	0.1474	***< 0.0001***	y = 9.4213 - 0.4374x	327	0.1408	***< 0.0001***	y = 7.2839 + 0.0275x
Alk	305	0.0679	***< 0.0001***	y = 2.1944 - 0.0488x	299	0.1267	***< 0.0001***	y = 1.9311 + 0.0043x
WaterT	330	0.1811	***< 0.0001***	y = 45.386 - 6.7122x	--	--	--	--

Thermal Response Parameters

Two parameters that demonstrated thermal-responsiveness based on cluster analysis and boxplots were pH and Chl-a (Figures 4-21 & 4-22). The primary clusters for pH were June – September and October – May (Figure 4-21A). The pH high season aligned well with the deep summer months of water temperature, and the low pH months of December – January likewise aligned with the deep winter months of water temperature. Chl-a clusters lined-up in similar fashion with patterns in water temperature. Regression analysis of pH with water temperature showed a higher R^2 than that of pH with flow at USGS 08065350 (Table 4-14). Cluster and regression analyses provided strong evidence that pH patterns were responding to temperature-driven processes in Lake Livingston, especially in the lower lake, since the amount of variation explained by temperature doubled to 31 percent when all stations were considered rather than just the upper two.

Temperature may, however, be an indirect driver of pH patterns. The principal driver of pH is likely biological, though temperature and the commensurate incident solar radiation ultimately drive lake algal populations. It is common in lakes with abundant algae, such as Lake Livingston, for diel DO and pH to range more widely during the summer than during the winter. During the summer, when primary producers are most active, photosynthesis drives up DO and pH during the day. At night respiration processes consume DO and respire CO_2, causing pH to lower along with DO. According to 24-h data from Lake Livingston, diel swings in DO and pH both increased in magnitude during July – September, parallel to monthly trends in Chl-a (Figures 4-23 & 4-24). Regressing pH with Chl-a also produced significant results (Figure 4-25).

During the last decade, Lake Livingston was classified hypereutrophic according to the Carlson TSI index (TCEQ, 2011), a fact well supported by the extremely high levels of nutrients throughout the lake described in this report and others (see Huang et al., 1973 and Pendergrass and Hauck, 2008). However, despite nutrient enrichment, excursions of pH and Chl-a were not as common in the upper lake as in the lower lake (see Figure 4-26 for spatial pH trends). A source with the TRA cited higher turbidity as the primary reason for reduced phytoplankton activity in the upper lake (Pendergrass and Hauck, 2008), and this is supported by the lake's strong longitudinal trend in TSS (Figure 4-27). In summary, temporal and spatial patterns, cluster analyses, regressions and historical nutrient enrichment all support the narrative that pH and Chl-a excursions are summer phenomena in the mid and lower lake driven by cultural eutrophication.

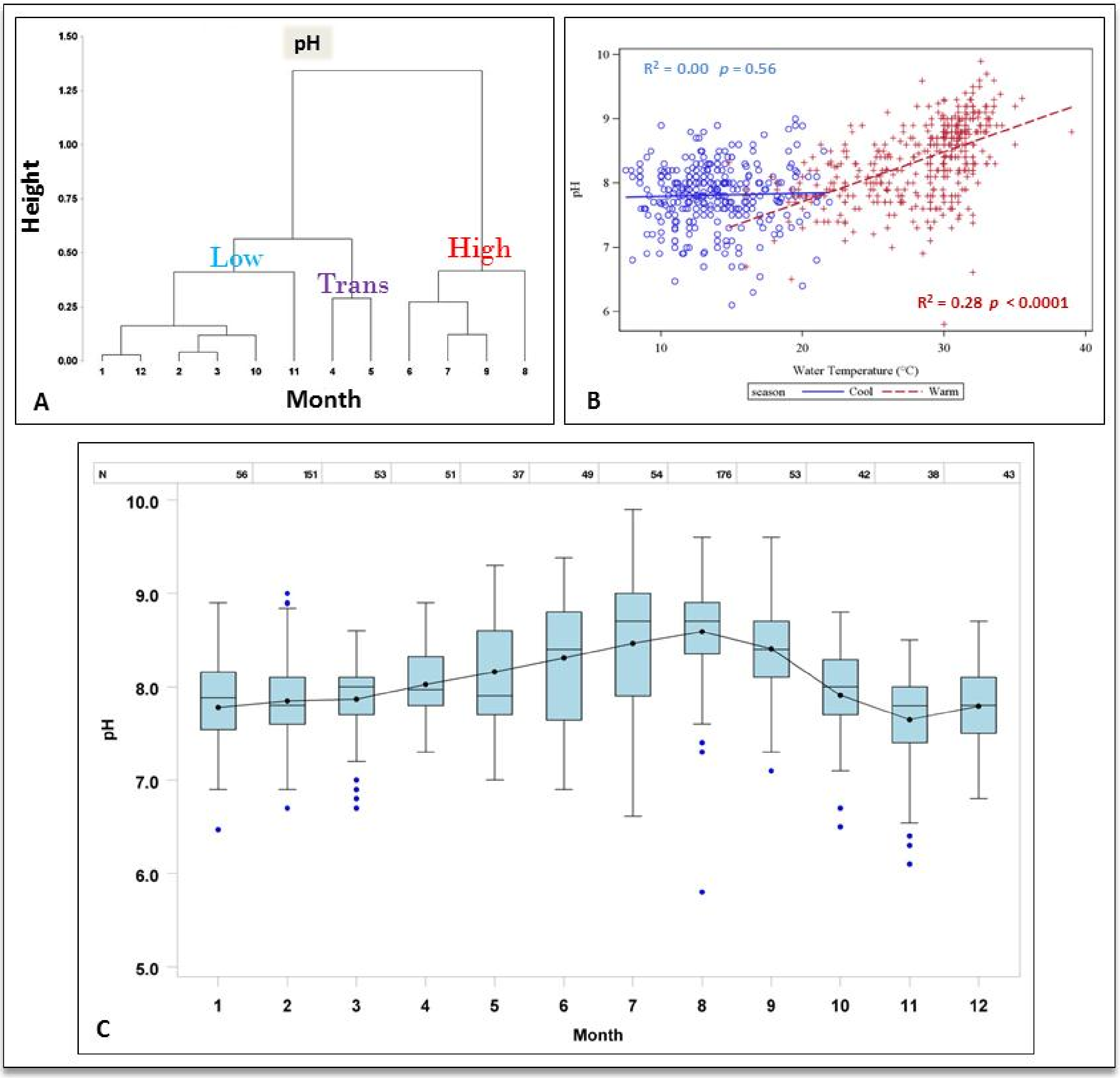

Figure 4-21 Cluster analysis of monthly means of pH, regression of pH with water temperature (B) and boxplot of pH by month (C) for primary Lake Livingston stations, years 1993 – 2005.

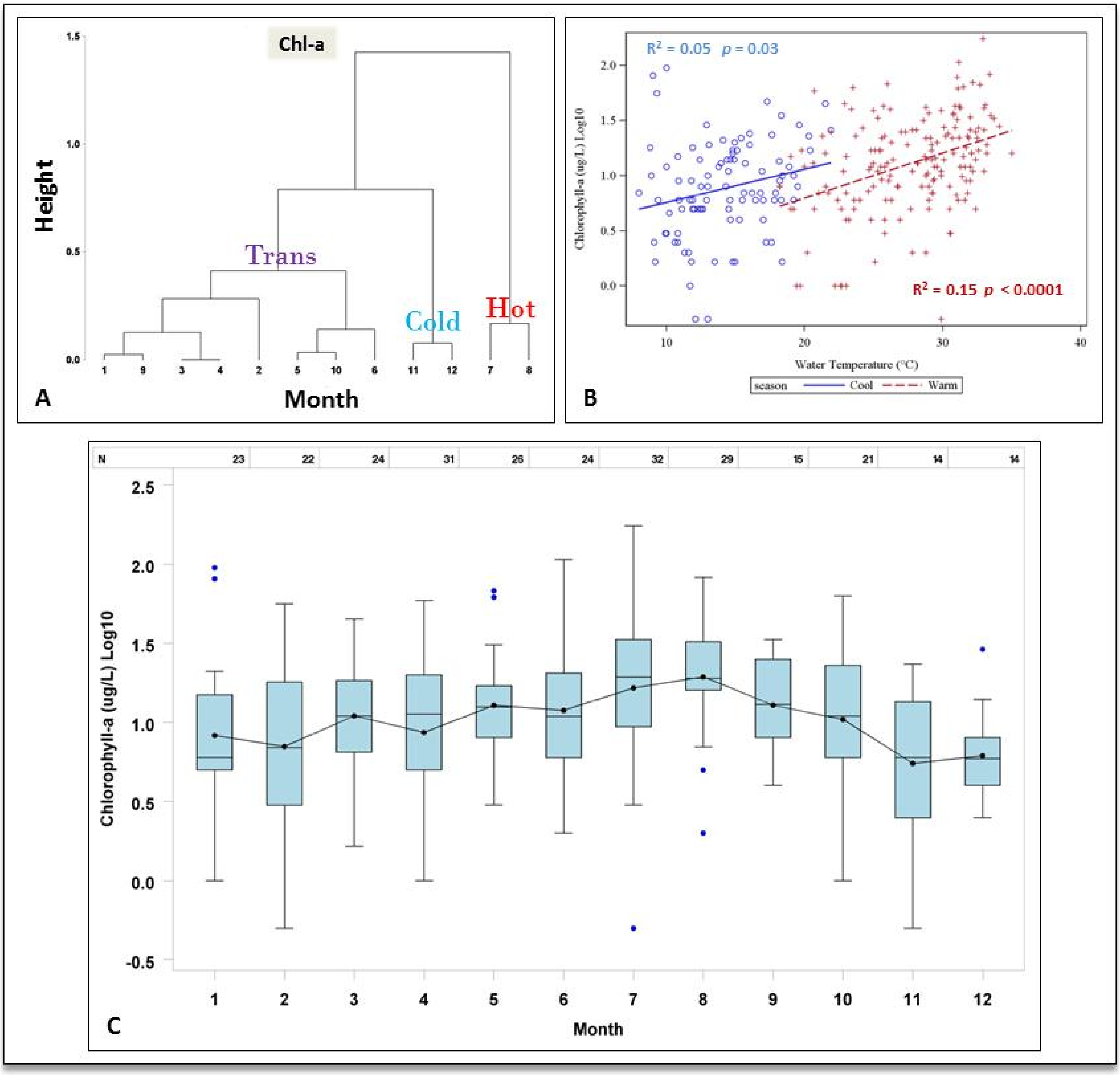

Figure 4-22 Cluster analysis of monthly means of Chl-a, regression of Chl-a with water temperature (B) and boxplot of Chl-a by month (C) for primary Lake Livingston stations, years 1993 – 2005. Chl-a was $\log_{10}$ transformed for regression analysis.

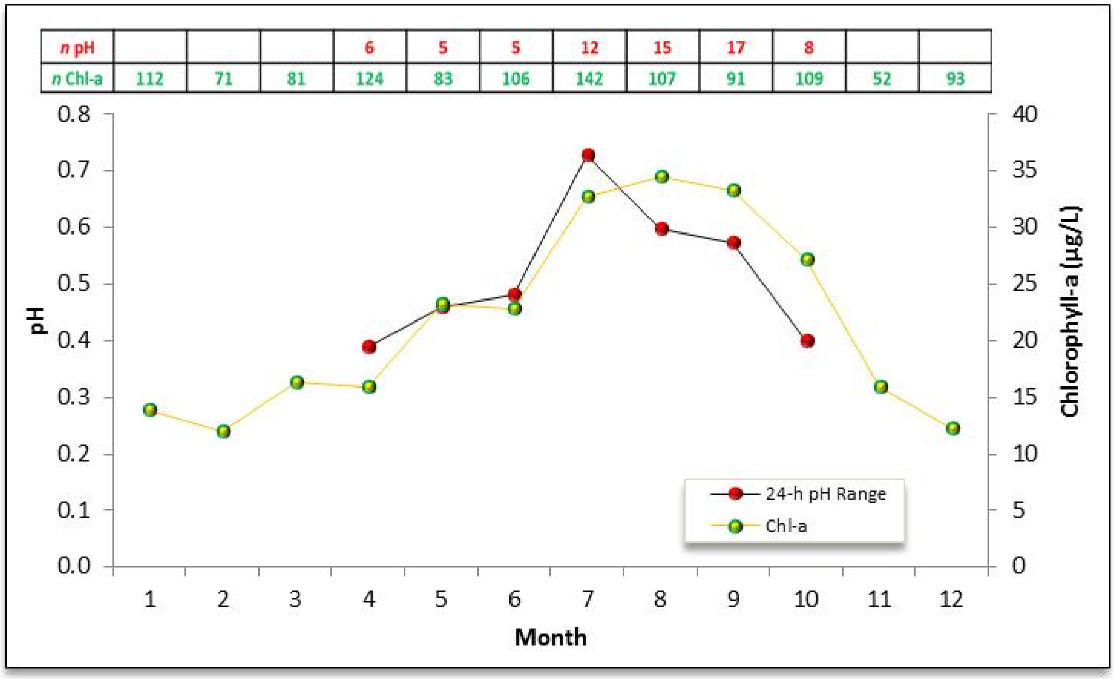

Figure 4-23 Monthly means of diel pH range (24-h pH max – 24-h pH min) and Chl-a Lake Livingston stations 10914, 10913, 14014, 10911, 14007, 14006, 14005, 10899 and 10909, years 1991 – 2010.

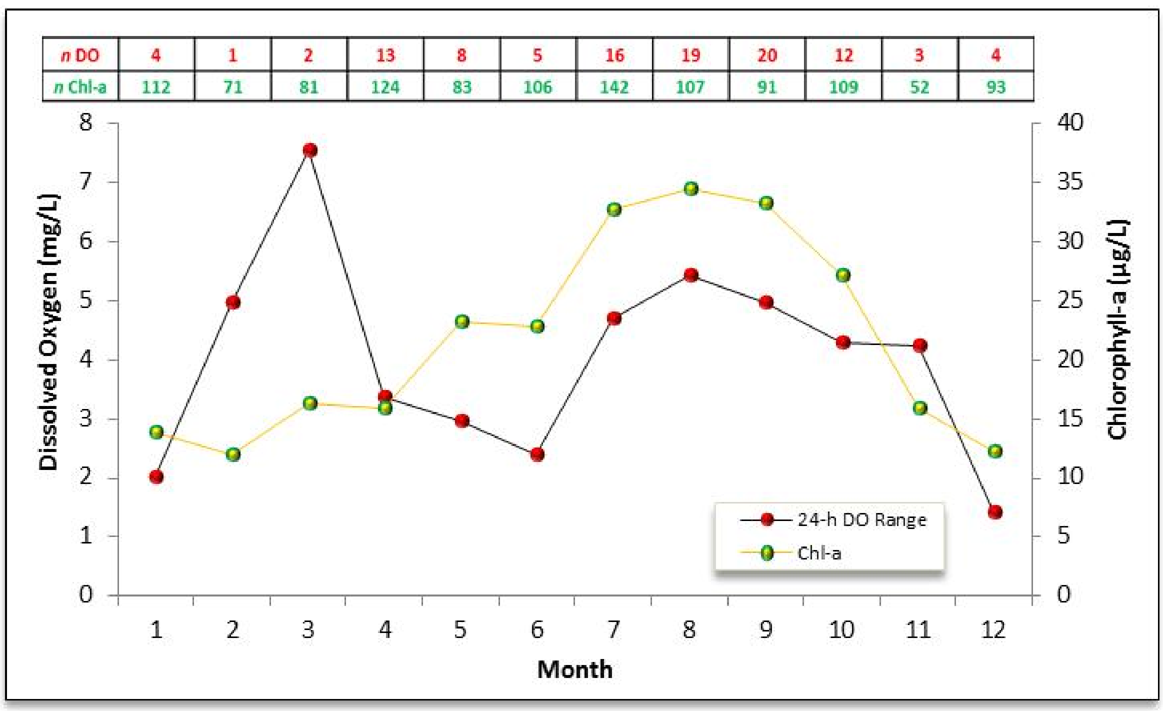

Figure 4-24 Monthly means of diel DO range (24-h DO max – 24-h DO min) and Chl-a for Lake Livingston stations 10914, 10913, 14014, 10911, 14007, 14006, 14005, 10899 and 10909, years 1991 – 2010. Anomalous high DO range values in February and March were likely the result of small sample size.

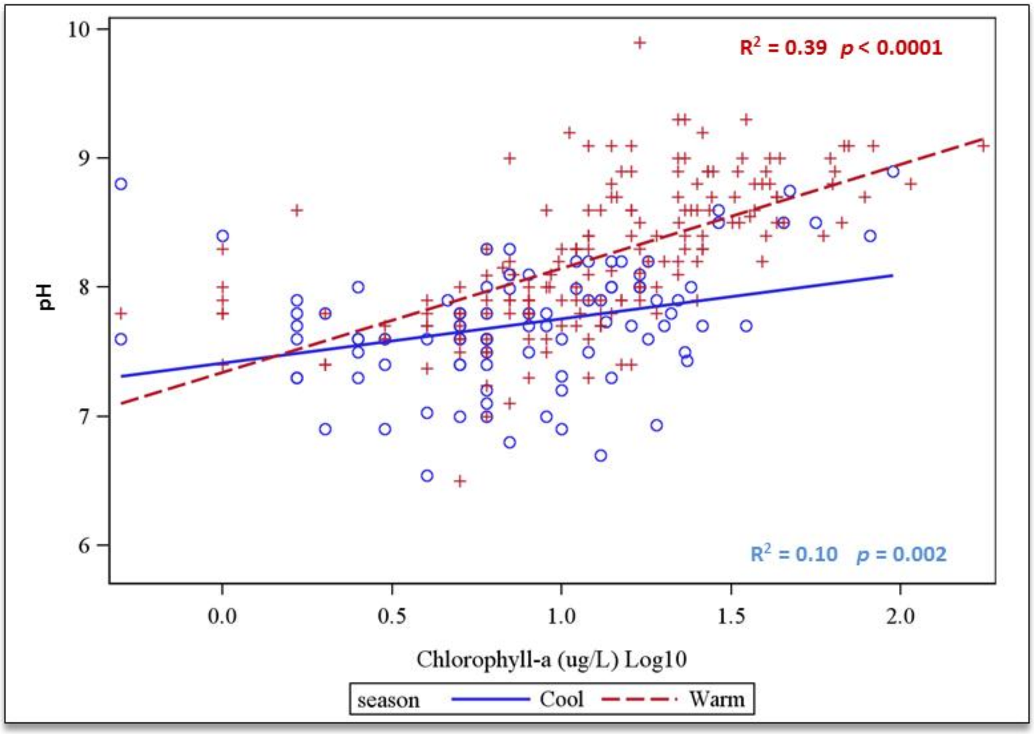

Figure 4-25 Regression of pH with Chl-a for primary Lake Livingston stations, 1993 – 2005.

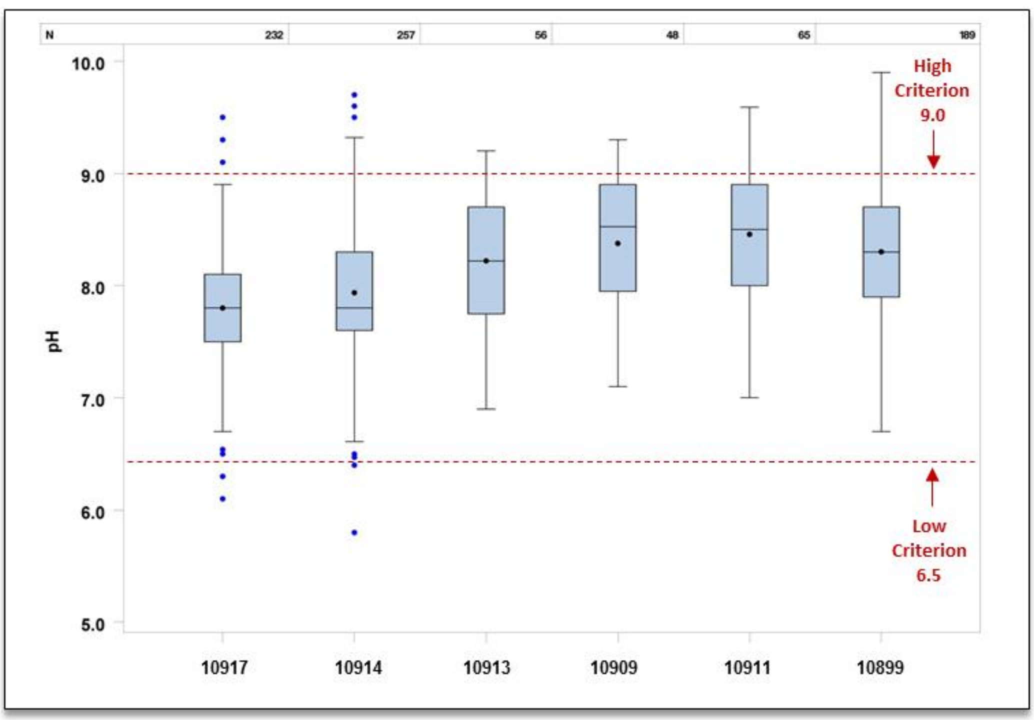

Figure 4-26 Spatial trends in pH in Lake Livingston, 1991 – 2011. Stations are ordered upstream to downstream, where 10917 is the uppermost station and 10899 is near the dam.

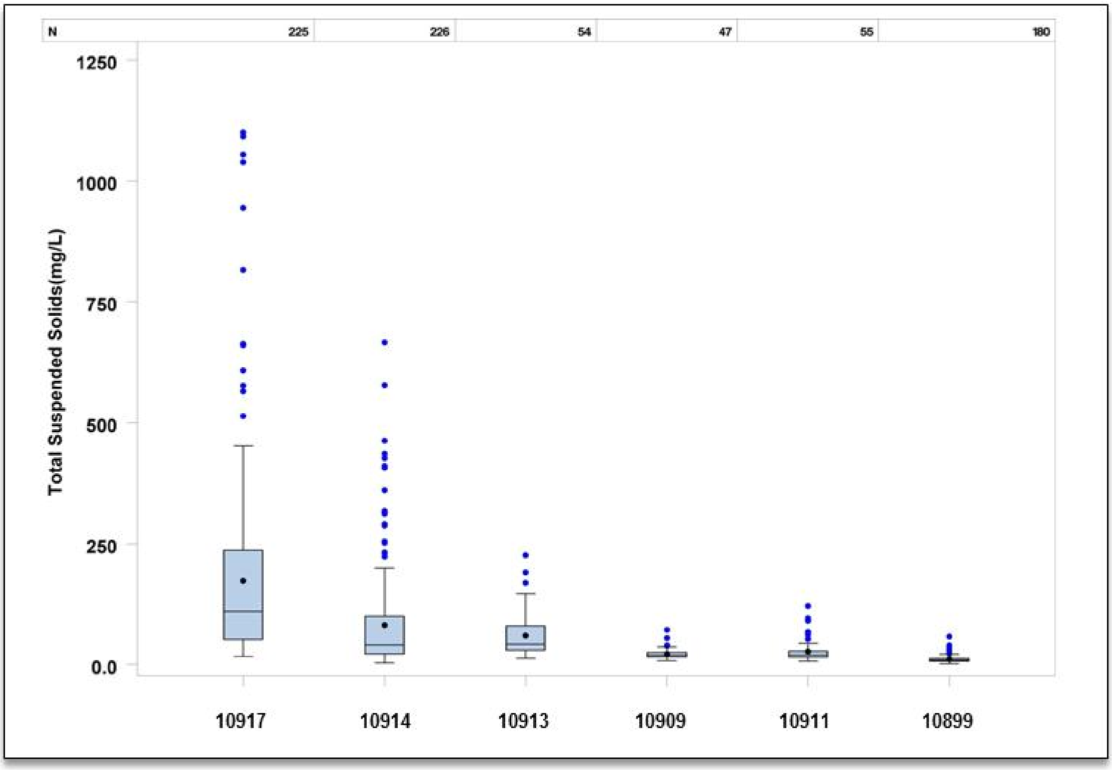

Figure 4-27 Spatial trends in TSS in Lake Livingston, 1991 - 2011. Stations are ordered upstream to downstream, where 10917 is the uppermost station and 10899 is near the dam.

Flow Response Parameters

The SO_4 response to Trinity River flow (USGS 08065350) was negative and significant with monthly clustering patterns that parallel Trinity River hydrology (Figure 4-28). Flow explained 21 percent of the variation in SO_4 concentrations when all Lake Livingston primary stations were included and 46 percent of the variation when only the upper two stations, 10917 and 10914, were evaluated ($p < 0.0001$; Table 4-14).

Flow-responsive parameters ought to show tighter clusters in the February – April and August – October periods, coinciding with the peaks and valleys of the flow cycle. SO_4, NO_3 and OP cluster March – April (hydrological peak) and September – October (hydrological valley) in separate tight groups (e.g., SO_4 in Figure 4-28A). Regressions of these nutrients to log-transformed flow at Trinity River near Crockett (USGS 08065350) showed that only SO_4 had both a significant correlation and a moderate R^2 when all primary Lake Livingston stations were grouped together (Table 4-14). However, when limited to the upper two stations, 10917 and 10914, 30 percent of NO_3 (Figure 4-29) and 35 percent of OP concentration variances were explained by flow at USGS 08065350. This was not surprising since Stations 10917 and 10914 are the closest to this flow gage (Figure 3-4; Table 3-4). These results were useful, however, for focusing attention on the fact that SO_4, NO_3 and OP concentrations in the upper lake were negatively and strongly correlated to Trinity River flow, suggesting the importance of point-source loadings from the DFW area. With distance downstream multiple other factors exert increasing influence on patterns in these constituents, including biological uptake by primary producers.

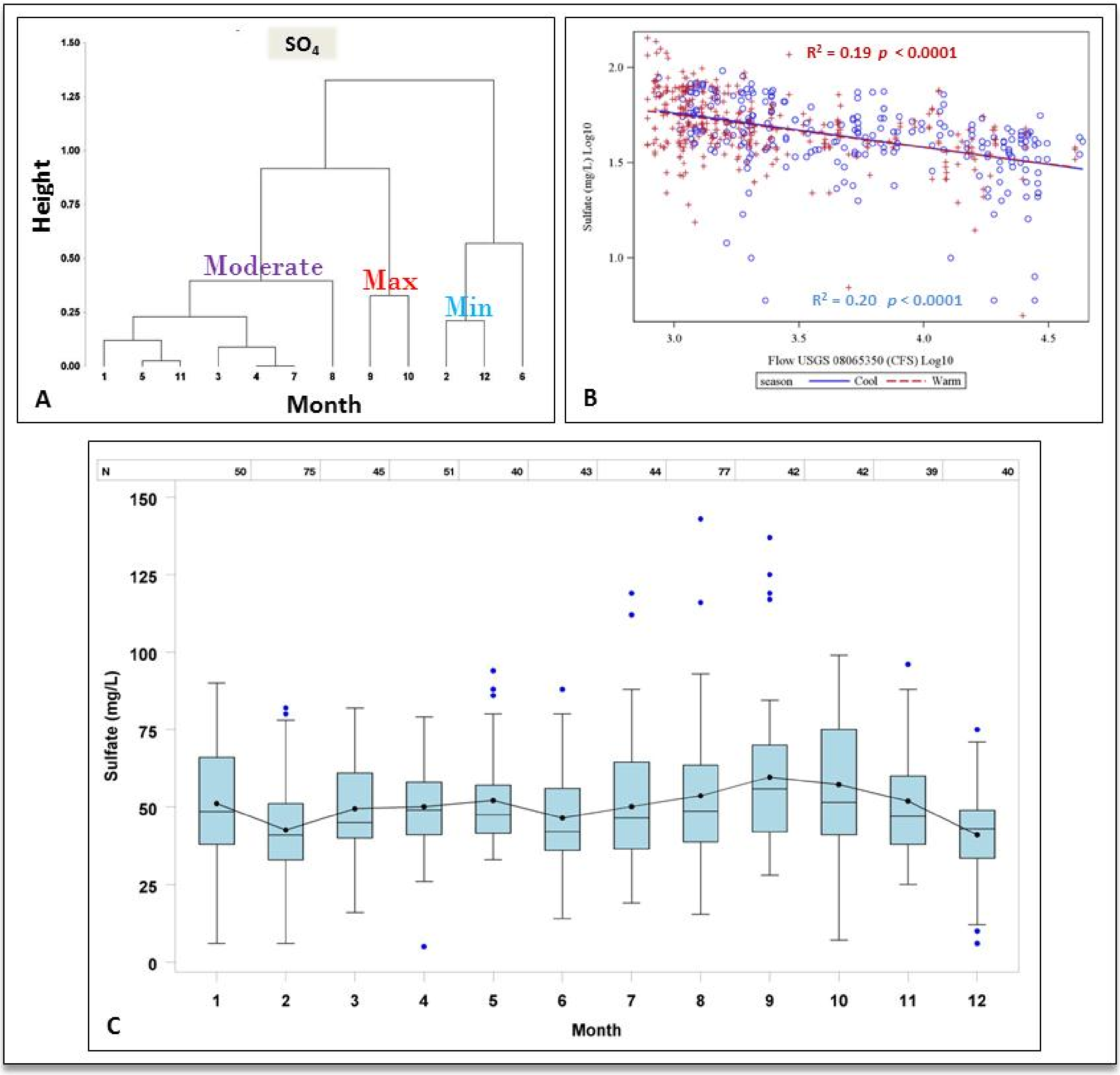

Figure 4-28 Cluster analysis of monthly means of SO_4, regression of SO_4 with flow (B; USGS 08065350) and boxplot of SO_4 by month (C) for primary Lake Livingston stations, years 1993 – 2005. Flow and SO_4 were log_{10}-transformed for regression analysis.

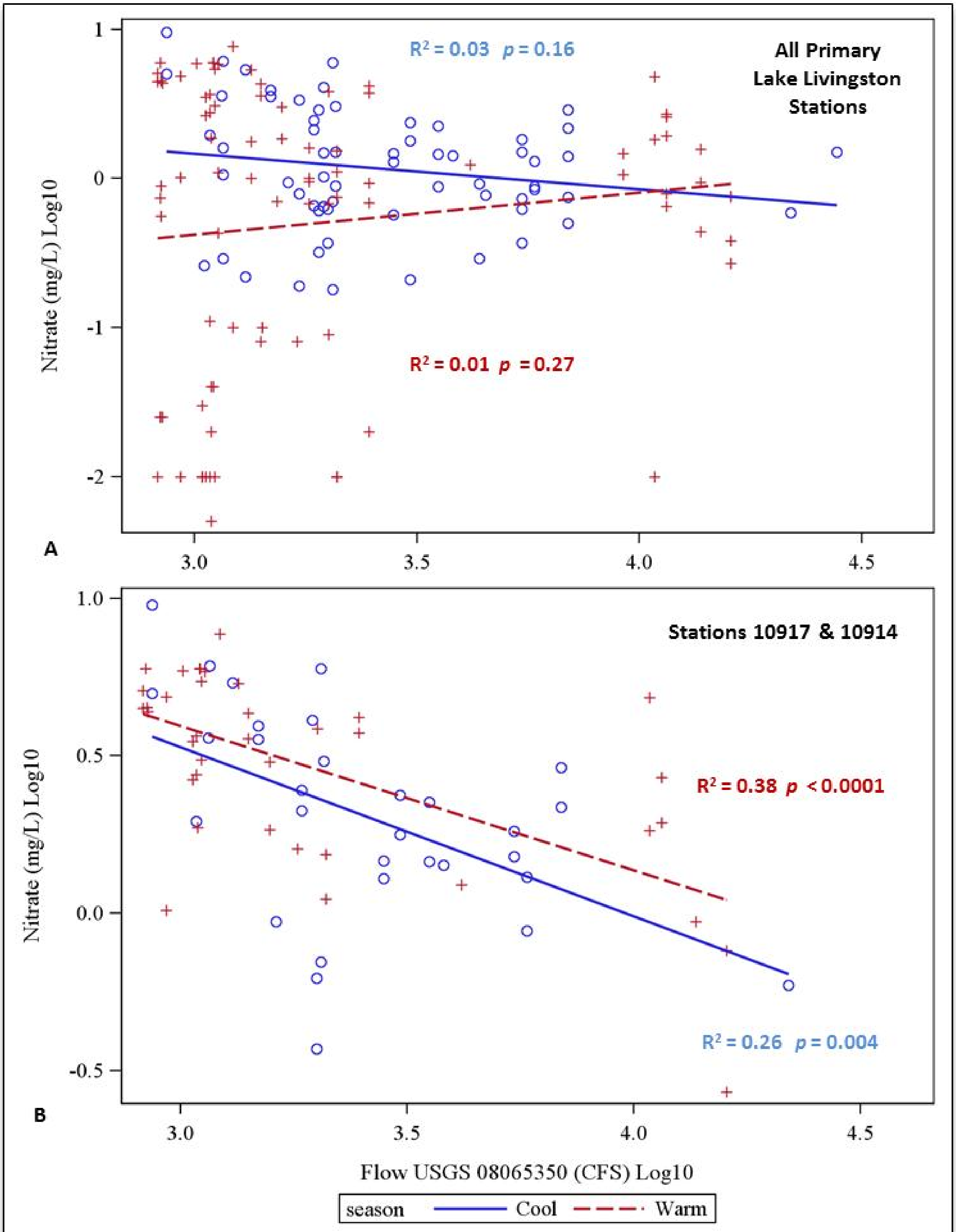

Figure 4-29 Regression of NO_3 with Trinity River flow (USGS 08065350), 1993 - 2005, for primary Lake Livingston stations (A) and Stations 10917/10914 (B).

In the upper lake, TSS, *E. coli*, and Fcoli were strongly and positively correlated to flow but negatively correlated to water temperature (Table 4-14); a pattern associated with nonpoint source loadings. Bacteria is likely a flow-responsive parameter and the correlation to water temperature largely coincidental because 1) cooler months coincided with months of higher flow and 2) R^2 values for bacteria versus flow increased dramatically when the analysis was limited to the stations closest to USGS 08065350 (Trinity River near Crockett; Tables 4-14).

Longitudinal Patterns in Trinity River – Lake Livingston

To evaluate longitudinal patterns along the continuum of the Trinity River near Dallas through Lake Livingston, median values of the key parameters were arranged by station from upstream to downstream (Table 4-15). This analysis integrates the separate spatial analyses presented earlier in this chapter for the Trinity River and Lake Livingston. Due to the prominence of the Trinity River inflows and loadings of key parameters to Lake Livingston (as further established in the next chapter), connectivity of the Trinity River to Lake Livingston was anticipated.

Many of the key water quality parameters demonstrated the anticipated decreases in concentration from the DFW area, downstream through the Trinity River, and generally even more pronounced declines through Lake Livingston. A combination of factors facilitate this decrease in median concentrations, including assimilative capacity of the system, dilution from contributing downstream watershed areas having fewer and smaller regulated point sources and a decreased percent cover of intensive land uses in the lower watershed than in the DFW area. Parameters exhibiting this decrease included NO_3, NO_{23}, OP, BOD_5 (limited spatial data), *E. coli* and Fcoli (Table 4-15). These parameters exhibited roughly a threefold decrease from the DFW area (Station 10937) to the lowermost station on the Trinity River (13690), but through the lake these parameters further decreased an order-of-magnitude in concentration. Within Lake Livingston, the relatively long retention period of about one year (see Figure 2-10) provides abundant time for biological uptake to "process" the listed bioavailable inorganic nutrient forms. Phytoplankton increased, as measured by Chl-a, and represents the biological response to uptake of inorganic nutrients. This, in turn, causes the documented increases in pH values measured in the lake. In contrast NH_3, another inorganic nutrient form, remained relatively constant from station to station, most likely representing the benefits of the enhanced nitrification treatments implemented at WWTFs in DFW by the mid-1980s. For *E. coli* and Fcoli, the large decrease in the downstream direction within Lake Livingston is likely a combination of settling of bacteria through the water column plus the disinfection afforded by the ultraviolet component of sunlight.

While SO_4 and Alky did not decrease along the Trinity River and within Lake Livingston as much as the other parameters discussed immediately above, there was still a notable decrease in both parameters. For SO_4 the result of this decrease within the lake was that median concentrations in the lower, near-dam areas of Lake Livingston were below the long-term average SO_4 criterion of 60 mg/L. Regarding Alky, which decreased from in-river concentrations of about 120 mg/L as $CaCO_3$ to 90 mg/L in the lower lake, the implications are reduced buffering capacity for which it is speculated that pH response to photosynthesis-respiration process could be increased by this decrease in buffering capacity.

Perhaps the most interesting and problematic longitudinal pattern to explain was for TSS (Figure 4-30 in addition to Table 4-15). The decrease noted longitudinally along Lake Livingston was what would be anticipated in any relatively quiescent water body due the physical settling of particulate matter. The primarily increasing TSS pattern along the Trinity River, however, was more difficult to explain, and this explanation must be considered no more than a logical hypothesis. The following combination of factors could explain what was observed along the Trinity River:

- low TSS concentrations in the effluent from the large regional WWTFs in the DFW area,
- the abundance of large lakes in the DFW area that effectively reduce the drainage area to the immediate area except during the largest storm runoff events that cause substantial releases from these reservoirs, and
- increasing drainage area in the downstream direction for the Trinity River.

Stringent effluent limits on TSS for WWTFs effectively reduce in-river concentrations through dilution of the higher background concentrations in the river. The two drainage area factors impact the length of response of the Trinity River to runoff events. In the Metroplex area the relatively small effective drainage area, as well as the high amount of impervious cover in that area, result in a rapid and relatively short-lived storm hydrograph whereas further downstream the response to rainfall events will result in a longer-lived storm hydrograph than further upstream. Since TSS concentrations increase with flow, albeit in a complex manner as discussed in Chapter 5, the longer-lived hydrographs further downstream afford more opportunities to be captured by the routine water quality monitoring than do shorter-lived storm hydrographs in the upper part of the study area.

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Table 4-15 Median values for key parameters at select stations in Trinity River and Lake Livingston, 1991 – 2010. Darker shades indicate higher value relative to station; stations in order of upstream to downstream; nd = no data, asterisk indicates $n < 3$; lowest n for shaded values was 9 for Chl-a at Station10920.

	Trinity River								***Lake Livingston***						
AU	805_04	805_03	805_02	805_01	804_07		804_04	804_01	0803_11	0803_10	0803_07	0803_06	0803_05	0803_01
Station	**10937**	**10934**	**10925**	**10924**	**10922 / 10921**	**10920**	**10919**	**13690**	**10917**	**10914**	**10913**	**10911**	**10909**	**10899**
NH_3	0.08	0.08	0.08	0.08	0.05	0.10	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.05
TKN	1.00	1.08	1.00	1.11	1.08	0.90	1.00	0.90	0.90	0.80	1.00	0.90	0.90	0.60
NO_3	7.56	7.35	6.60	4.26	*	nd	1.48	3.02	2.69	2.26	0.74	0.42	0.03	0.19
NO_{23}	6.85	5.80	5.93	5.54	5.59	4.63	3.91	2.65	2.47	1.63	0.76	0.36	0.05	0.17
OP	0.95	0.94	0.87	0.85	0.79	0.89	0.49	0.30	0.28	0.20	0.14	0.09	0.05	0.05
TP	1.10	1.06	1.11	1.01	1.05	0.85	0.81	0.62	0.58	0.40	0.28	0.20	0.16	0.14
Chl-a	10.0	9.9	12.0	5.8	12.1	8.8	9.7	9.0	8.0	10.0	28.0	33.9	30.0	14.8
SO_4	79	75	70	69	68	nd	65	57	56	52	51	46	36	40
E. coli	128	414	101	121	68	nd	76	59	48	28	6	4	8	2
TSS	21	52	86	109	122	*	158	120	110	41	42	20	19	9
BOD_5	nd	1.9	1.6	nd	1.6	nd	nd	1.8	nd	nd	nd	nd	nd	nd
Fcoli	nd	460	360	77	49	nd	70	120	100	50	20	10	30	10
pH	7.7	7.6	7.8	7.5	7.9	7.8	7.8	7.8	7.8	7.8	8.2	8.5	8.5	8.3
Alky	nd	118	122	126	128	nd	121	111	110	104	101	98	84	94

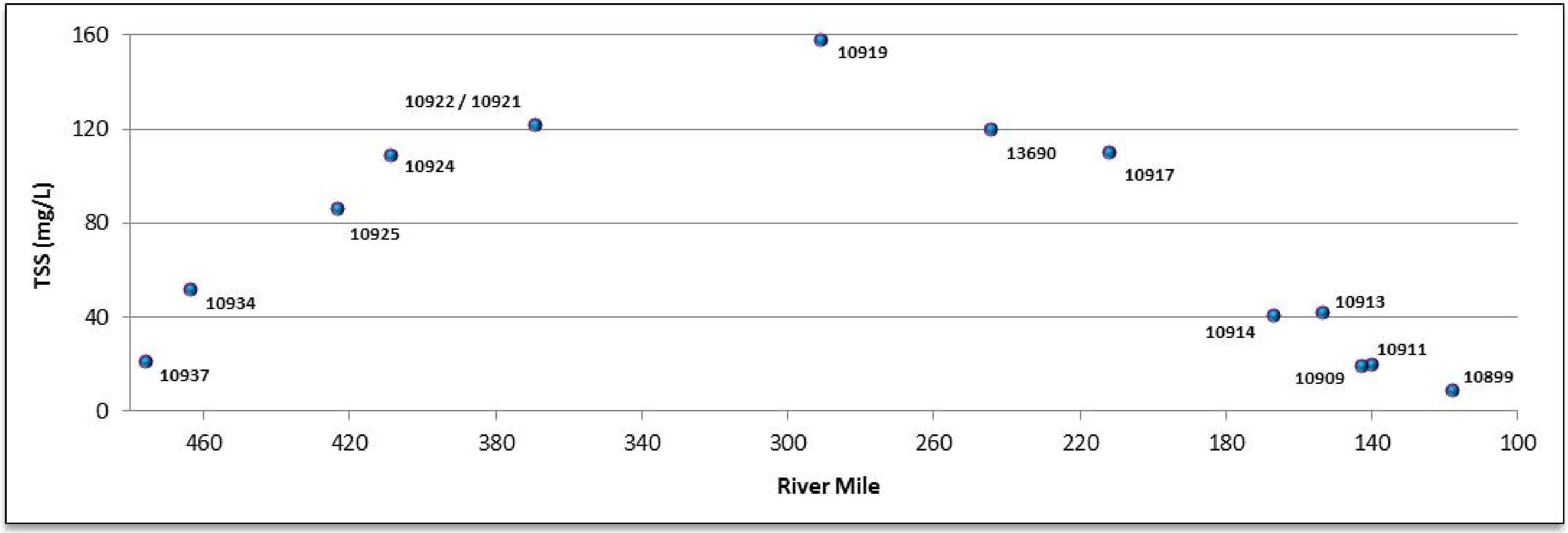

Figure 4-30 Median values of TSS (mg/L) in select Trinity River and Lake Livingston stations, 1991 – 2010. Stations and locations of major reservoir inflow points are labeled.

Historical and Recent Trends in Fish Populations of the Trinity River and Lake Livingston

Historically, poor water quality, hypoxia and toxic levels of NH_3 in particular, severely impacted fish communities in the Trinity River between Dallas and Lake Livingston (EIH, 2009). Fish kills were common until the mid-1980s. To wit, 13 fish kills were documented between 1970 and 1985 in the Trinity River between Dallas and Lake Livingston. Since that time, efforts to reduce organic loading and raise DO levels have enabled Trinity River fish populations to rebound in both abundance and diversity though the modern population structure has shifted from native riverine species to exotic lentic species (EIH, 2009). Riverine specialist species and migratory fish have been badly hampered by fragmentation of the river (Thomas et al., 2007)—the Trinity River is among the most fragmented systems in Texas (EIH, 2009). Populations of native fluvial species of Percide, Itctaluridae and Cyprinidae have been replaced by exotic lentic species such as mosquitofish (*Gambusia affinis*) and shad (Clupeidae). Migratory fish, such as the paddlefish (*Polyodon spathula*) and the American eel (*Anguila rostrata*), have been nearly extirpated from the Trinity River above Lake Livingston dam due largely to the migration impediments of dams and reduction of riverine habitat caused by impoundments (Thomas et al., 2007; PBS&J, 2008).

A year-long seasonal survey conducted by PBS&J in 2007 - 2008 (PBS&J, 2008) counted 26 fish species in Lake Livingston and only 2 were collected exclusively in the lake: tadpole madtom (*Noturus gyrinus*) and redear sunfish (*Lepomis microlophus*). Sport fish were quite abundant in the lake, particularly striped bass (*Morone saxatilis*) which were common throughout the year. Blue catfish (*Ictalurus furcatus*), white bass (*M. chrysops*), largemouth bass (*Micropterus salmoides*) and channel catfish (*I. punctatus*) were also abundant. Not surprisingly, the dominance of cosmopolitan fish species in Lake Livingston is similar to the Trinity River.

Fish abundance and diversity in the Trinity River between Dallas and Lake Livingston dam are not a present concern as water quality is sufficient to support reproducing and somewhat resilient populations. Water quality, in turn, is not threatened greatly by a shift towards generalist fish species. However, increases in the relative abundance of tolerant exotics is of general ecological concern as they impact fisheries management, food webs, and typically reduce native aquatic biological diversity.

Chapter 5
Pollutant Loadings to Lake Livingston

Development of Loading Estimates

Loadings to Lake Livingston were developed based on estimates provided by the LOADEST FORTRAN program available from the USGS (2012). Based on time series data, generally paired concentration and flow values, the LOADEST program aids the user in selecting an appropriate regression model for estimating loads for a given time period. A suite of nine regression models based on concentration and time is provided in LOADEST (Table 5-1). These nine models are based on a long history of efforts by a number of different researchers regarding development of empirical methods for estimating constituent loads (e.g., Cohn et al., 1992). Streamflow is the major component driving loadings, while including parameters associated with time allows the regression model to evaluate potential temporal patterns. LOADEST also includes an option to incorporate additional parameters and a user-defined model, if such is appropriate for a given fluvial system. For loading estimates for Lake Livingston, the LOADEST program was allowed to automatically select the best fit model from the nine regression models provided.

Table 5-1 Regression models considered by LOADEST in estimating constituent loadings. [ln*Q* = ln(streamflow) - center of ln(streamflow); *dtime* = decimal time - center of decimal time] Source: Runkel, et al. (2004).

Model Number	Regression Model
1	$a0 + a1 \ln Q$
2	$a0+a1 \ln Q+a2 \ln Q2$
3	$a0+a1 \ln Q+a2 dtime$
4	$a0+a1 \ln Q+a2 \sin(2\pi dtime)+a3 \cos(2\pi dtime)$
5	$a0+a1 \ln Q+a2 \ln Q2+a3 dtime$
6	$a0+a1 \ln Q+a2 \ln Q2+a3 \sin(2\pi dtime)+a4 \cos(2\pi dtime)$
7	$a0+a1 \ln Q+a2 \sin(2\pi dtime)+a3 \cos(2\pi dtime)+a4 dtime$
8	$a0+a1 \ln Q+a2 \ln Q2+a3 \sin(2\pi dtime)+a4 \cos(2\pi dtime)+a5 dtime$
9	$a0+a1 \ln Q+a2 \ln Q2+a3 \sin(2\pi dtime)+a4 \cos(2\pi dtime)+a5 dtime+a6 dtime2$

Based on the availability of paired concentration and flow data, loadings were developed for two stations: one on the Trinity River at Crockett pairing daily flow data from USGS station 08065350 with concentration data from TCEQ station 13690, and the other on Bedias Creek near Madisonville pairing daily flow data from USGS station 08065800 with concentration data from TCEQ stations 10702 and 10703 (see Figure 3-3 and 3-4). Data from 1970 through 2010 were used in the calibration of loadings for Bedias Creek, while only data from 1991 through 2010 were used for calibration of loadings for the Trinity River due to changes in flow over time with expansion of the urban population upstream of Crockett. For consistency, total loadings to Lake Livingston were estimated for 1991 through 2010.

The total drainage area at the dam for Lake Livingston, including the surface water, covers 16,583 square miles. While the surface area of Lake Livingston varies somewhat over time, it averages about 130 square miles. The drainage area of the Trinity River station near Crockett, Texas covers 13,911 square miles or about 85% of the reservoir drainage area. The intervening or lower drainage area below the Trinity River station near Crockett is about 2,542 square miles of which the station on Bedias Creek covers 321 square miles. The only other USGS station representing flows into Lake Livingston was station 08066170 on Kickapoo Creek near Onalaska, Texas. While daily flow data were available for Kickappo Creek back to 1965, very limited water quality data were available for creek. A TCEQ water quality monitoring station (10695) is located on Kickapoo Creek, but it had insufficient data for the variables of interest to be included in the data analysis in Chapter 4 and for loading estimates herein.

To estimate loadings to Lake Livingston, the watershed was divided into two distinct areas as follows:

1) the upper area of the watershed represented by the drainage of the Trinity River near Crockett, Texas , and
2) the lower area of the watershed, below the Trinity River station at Crockett, representing the remaining drainage area near Lake Livingston.

For the upper area, estimated daily loadings for the Trinity River near Crockett were used as calculated from LOADEST. For the lower area, estimated loadings for Bedias Creek were extrapolated by being multiplied by a drainage area ratio ([2,542 – 130]/321 = 7.51) as the best estimate. Total loadings to Lake Livingston were calculated as the sum of the upper area (loadings for the Trinity River near Crockett) and the lower area (the extrapolated loadings for Bedias Creek). The estimated loadings to Lake Livingston consider only the drainage area contributions and not any direct deposition from rainfall and dry material directly to the water body.

Ten constituents were evaluated for loadings (Table 5-2). The LOADEST program does consider left-censored data or values below (<) the reporting limit in developing load estimations, but does not handle multiple censoring levels well. Data for TCEQ stations 10702, 10703 and 13690 were largely uncensored, but for a few constituents, where at least five percent of values were indicated as less than, a censoring value was added to the input dataset (Table 5-2). Also, only fecal coliform values were available for the TCEQ stations 10702 and 10703 on Bedias Creek. These fecal coliform values were converted to *E. coli* by multiplying them by the ratio of geometric mean criterion for fecal coliform and *E. coli* set by TCEQ (126/200 = 0.63).

The residuals of load versus streamflow from the regression model selected by LOADEST program (Table 5-3) were evaluated to determine if the normality assumption was met along with evaluation of the normal probability plot correlation coefficient (PPCC). Values for PPCC closer to 1.0 indicate that the distribution of residuals is approximately normal. In all cases, except for NH_3 for station 13690, the assumption of a normal distribution of residuals was accepted. At station 13690, the large number of censored values made it difficult to meet statistical assumptions associated with regression modeling, but the regression model selected by LOADEST was still used as a "best estimate" of NH_3 loadings. For all LOADEST regression models, the adjusted maximum likelihood estimation (AMLE) method was used for estimating loads, as recommended by the programming documentation (Runkel et al., 2004).

Table 5-2 Constituents and censored values used with LOADEST.

Constituent	Stations 10702 and 10703		Station 13690	
	% < Values	Censoring Value for LOADEST	% < Values	Censoring Value for LOADEST
BOD_5	0%	None	0%	None
Chl-a	15%	2.5 µg/L	13%	2.5 µg/L
E. coli [a]	1%	None	2%	None
NH_3	5%	0.05 mg/L	56%	0.05 mg/L
NO_3	7%	0.05 mg/L	1%	None
OP	18%	0.05 mg/L	4%	None
TP	3%	None	0%	None
SO_4	3%	None	0%	None
TKN	0%	None	1%	None
TSS	1%	None	0%	None

a. Only fecal coliform values were available for the TCEQ stations 10702 and 10703 on Bedias Creek. These fecal coliform values were converted to *E. coli* by multiplying them by the ratio of geometric mean criterion for fecal coliform and *E. coli* set by TCEQ (126/200 = 0.63).

LOADEST Results, Loading Estimates and Discussion

Most of the regression models selected included a time and periodic component as indicated by the sine and cosine parameters in model numbers 4 and 6 through 9 (Table 5-1). Only BOD_5 for Bedias Creek and NO_3 for the Trinity at Crockett indicated a best-fit regression model that included only flow parameters (Table 5-3). A large component in the periodicity indicated for time is likely associated with variability in flow. The volume of flow associated with the upper and lower watershed areas showed generally higher streamflows during the winter and spring than in the summer and fall (Figures 5-1 and 5-2).

Table 5-3 Regression model number selected by LOADEST and normality evaluation. Model number refers to the selected model as shown in Table 5-1.

Constituent	Bedias Creek		Trinity at Crockett	
	Regression Model and R^2	PPCC	Regression Model and R^2	PPCC
BOD_5	Model 1, R^2=0.98	0.8630	Model 7, R^2=0.91	0.9938
Chl-a	Model 9, R^2=0.92	0.9904	Model 9, R^2=0.57	0.9946
E. coli [a]	Model 5, R^2=0.89	0.9915	Model 8, R^2=0.71	0.9794
NH_3	Model 9, R^2=0.96	0.9858	Model 7, R^2=0.54	0.8265
NO_3	Model 9, R^2=0.96	0.9942	Model 1, R^2=0.30	0.9178
OP	Model 9, R^2=0.97	0.9933	Model 7, R^2=0.38	0.9473
TP	Model 8, R^2=0.98	0.9846	Model 7, R^2=0.73	0.9875
SO_4	Model 9, R^2=0.98	0.9883	Model 9, R^2=0.91	0.9216
TKN	Model 5, R^2=0.99	0.9653	Model 6, R^2=0.92	0.9845
TSS	Model 6, R^2=0.98	0.9911	Model 6, R^2=0.91	0.9952

a. Only fecal coliform values were available for the TCEQ stations 10702 and 10703 on Bedias Creek. These fecal coliform values were converted to *E. coli* by multiplying them by the ratio of geometric mean criterion for fecal coliform and *E. coli* set by TCEQ (126/200 = 0.63).

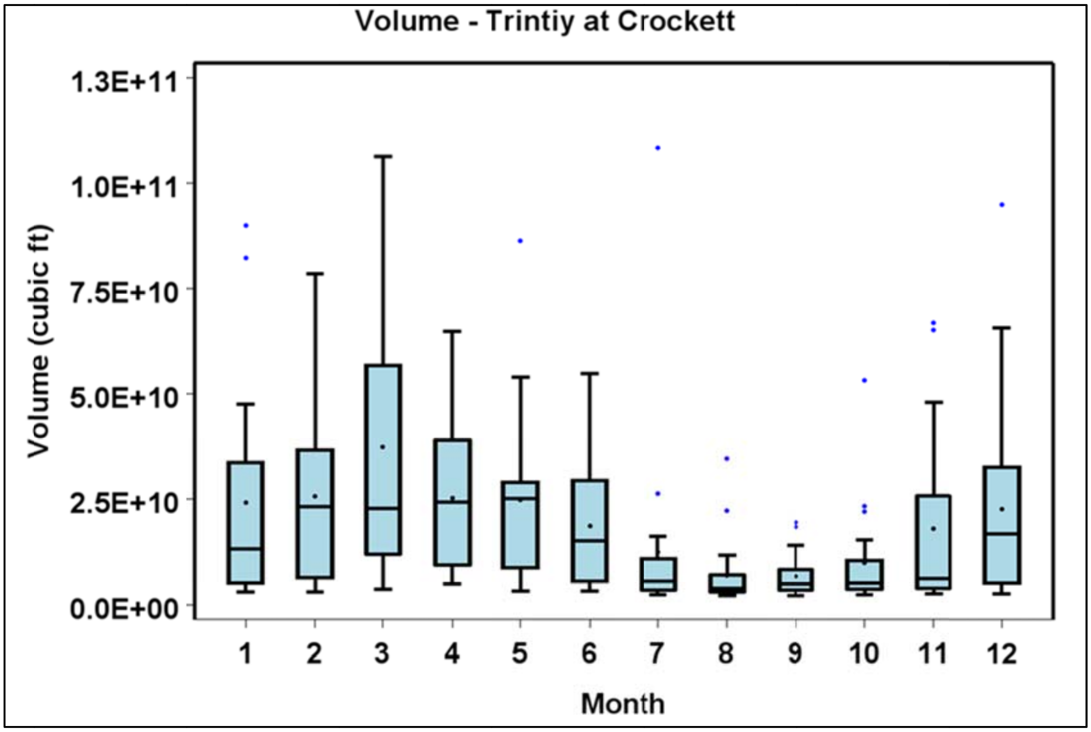

Figure 5-1 Box-and-whisker plots of the monthly volume of flow for 1991-2010 for the upper watershed area represented by the USGS station 08065350 located on the Trinity River near Crockett, Texas.

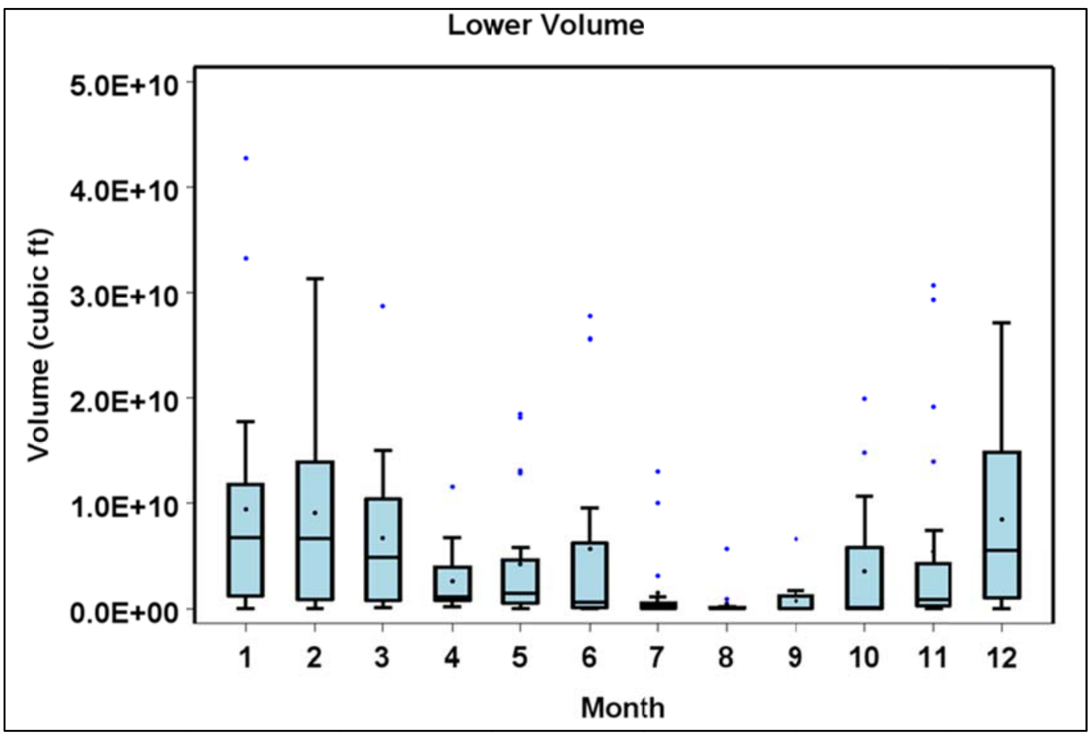

Figure 5-2 Box-and-whisker plots of the monthly volume of flow for 1991-2010 for the lower watershed area extrapolated from the USGS station 08065800 located on Bedias Creek.

The volume of water associated with the drainage area on the Trinity River above Crockett and for Bedias Creek when normalized on a per-area basis show the variability in the contributing areas by year as influenced largely by spatial and temporal variation in precipitation and the appreciable wastewater facility discharges from the DFW area (Figure 5-3).

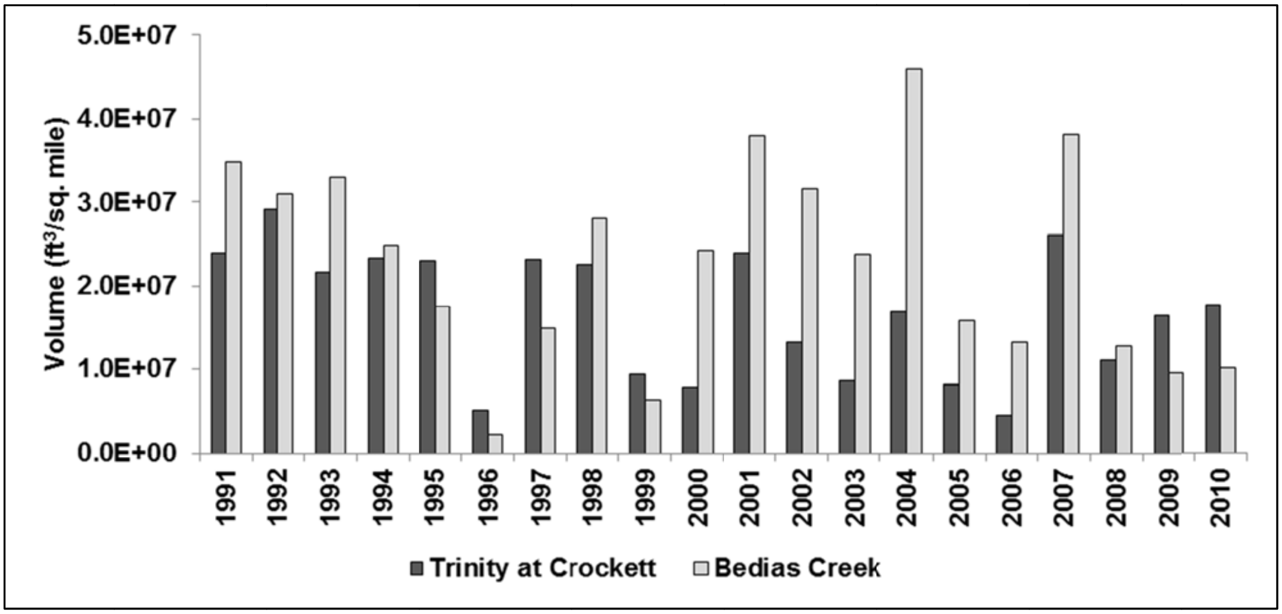

Figure 5-3 Annual volume of streamflow normalized per unit area for the Trinity River near Crockett and Bedias Creek.

By far the largest portion of the water flowing into Lake Livingston comes from the Trinity River with the flow from the Trinity River at Crockett representing on average about 80 percent of the total flow (Figure 5-4).

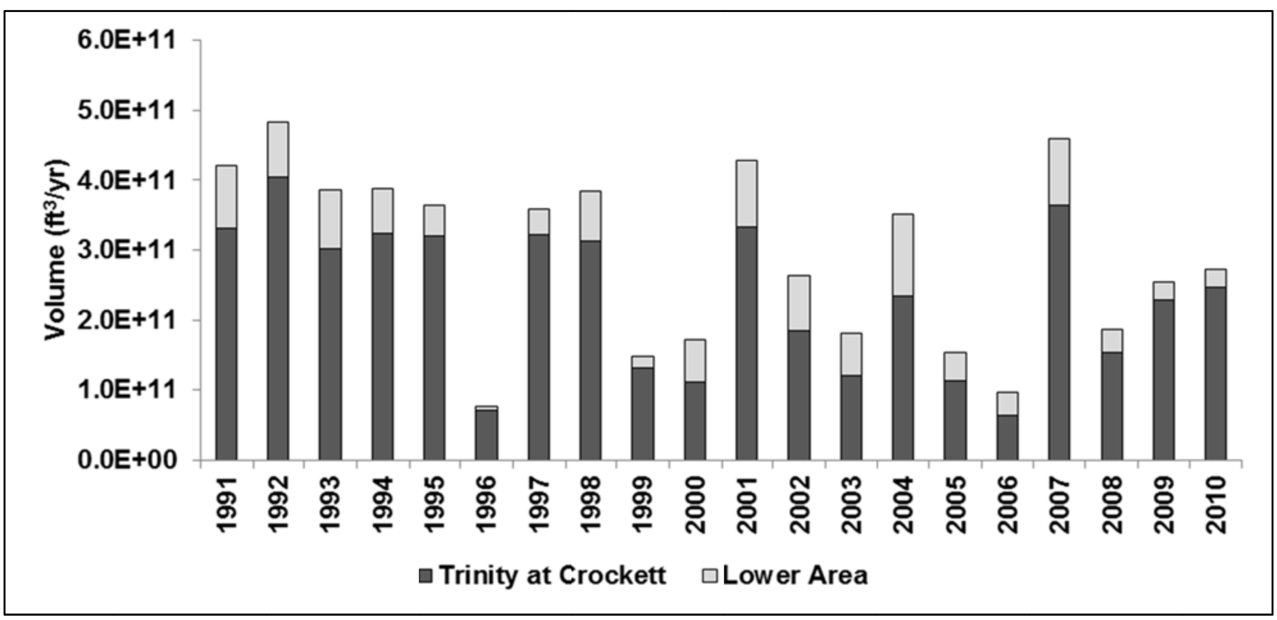

Figure 5-4 Annual volume of streamflow estimated to enter Lake Livingston from the Trinity River near Crockett and the lower watershed area below Crockett.

Given the year to year variability in flow, estimated loadings to Lake Livingston varied greatly over the 20-yr period evaluated (Table 5-4 and Figures 5-5 through 5-11). As might be anticipated, on average the percent loading from the Trinity River at Crockett was closely related to the percent volume of flow for this location. On average 88 to 89 percent of total annual loadings of OP, TP, SO_4 and TSS were associated with the Trinity River at Crockett.

Table 5-4 Basic statistics on annual LOADEST loading estimates 1991-2010.

Constituent	Units	Statistic	Trinity at Crockett	Lower Area	Total Loading
BOD_5	tons	Mean	14,267	5,055	19,322
		Median	14,361	5,308	20,536
		Standard Deviation	6,129	2,665	7,646
		Minimum	3,802	525	4,327
		Maximum	27,944	10,157	36,387
Chl-a	tons	Mean	74.24	2.10	76.34
		Median	68.94	1.98	70.69
		Standard Deviation	46.60	1.01	46.82
		Minimum	25.77	0.56	26.55
		Maximum	197.88	4.49	200.21
E. coli	colonies	Mean	8.08.E+14	6.72E+14	1.48E+15
		Median	4.86.E+14	6.91E+14	1.39E+15
		Standard Deviation	6.17.E+14	4.28E+14	8.07E+14
		Minimum	8.77.E+13	2.18E+13	2.89E+14
		Maximum	2.03.E+15	1.45E+15	2.71E+15
NH_3	tons	Mean	321	149	470
		Median	241	45	267
		Standard Deviation	200	218	397
		Minimum	71	1	75
		Maximum	792	719	1,368
NO_3	tons	Mean	10,850	921	11,771
		Median	11,196	924	12,208
		Standard Deviation	2,003	556	2,429
		Minimum	7,289	93	7,614
		Maximum	13,429	1,726	15,069
OP	tons	Mean	1,375	185	1,560
		Median	1,284	196	1,559
		Standard Deviation	388	104	467
		Minimum	795	28	884
		Maximum	2,035	340	2,334
TP	tons	Mean	3,793	541	4,335
		Median	3,646	557	4,504
		Standard Deviation	1,489	298	1,636

Constituent	Units	Statistic	Trinity at Crockett	Lower Area	Total Loading
		Minimum	1,423	56	1,813
		Maximum	6,288	1,205	6,873
SO_4	tons	Mean	285,442	34,827	320,270
		Median	297,659	35,381	336,586
		Standard Deviation	94,020	16,989	106,631
		Minimum	125,627	7,460	139,060
		Maximum	416,186	60,737	474,330
TKN	tons	Mean	6,463	2,156	8,618
		Median	6,712	2,212	9,086
		Standard Deviation	2,742	1,233	3,655
		Minimum	1,906	191	2,418
		Maximum	10,719	4,038	14,135
TSS	tons	Mean	1,609,918	195,848	1,805,765
		Median	1,856,589	208,721	1,979,966
		Standard Deviation	750,948	119,558	820,816
		Minimum	326,095	12,286	463,695
		Maximum	2,798,960	395,820	3,119,129

Biological oxygen demand indicated a larger percent loading from the lower area than was directly proportional to flow indicating that longer travel times likely allow for a larger assimilative capacity of BOD_5 along the Trinity River than for smaller tributaries nearer Lake Livingston (Figure 5-5).

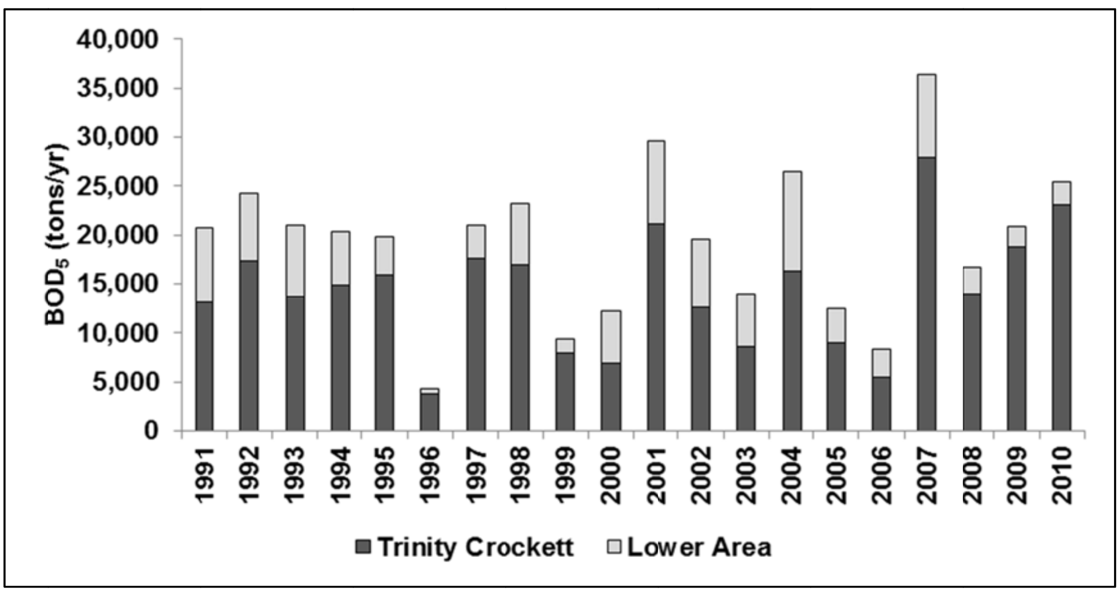

Figure 5-5 Annual estimated loading to Lake Livingston from the Trinity River at Crockett and the lower watershed area below Crockett of BOD_5

With regard to Chl-a, only about 3 percent of the total loading was estimated from the lower watershed area compared to the area represented above the Trinity River near Crockett (Figure 5-6).

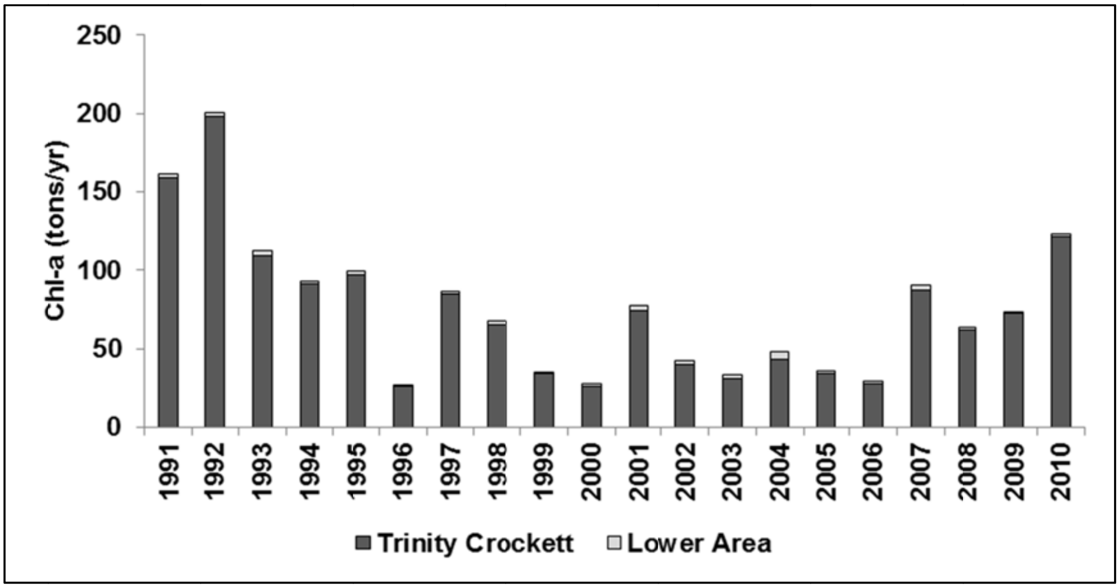

Figure 5-6 Annual estimated loading to Lake Livingston from the Trinity River at Crockett and the lower watershed area below Crockett of Chl-a.

Bacteria represented as colonies of *E. coli* showed almost a 50 to 50 split in contribution between the Trinity River near Crockett and the lower watershed area (Figure 5-7). Bacterial die-off in transport may ameliorate the water along the Trinity River prior to entering Lake Livingston compared to smaller creeks nearer the lake, which would have shorter transport times. While it appears that more *E. coli* may be contributed by areas closer to Lake Livingston, these estimates for *E. coli* loadings need to be interpreted carefully in that fecal coliform values were "converted" to *E. coli* for measurement collected on Bedias Creek based on a simple ratio. Measurements of *E. coli* and fecal coliform along Bedias Creek would help refine the conversion factor used in calculating these bacteria loadings and give a better understanding of where contributions are occurring.

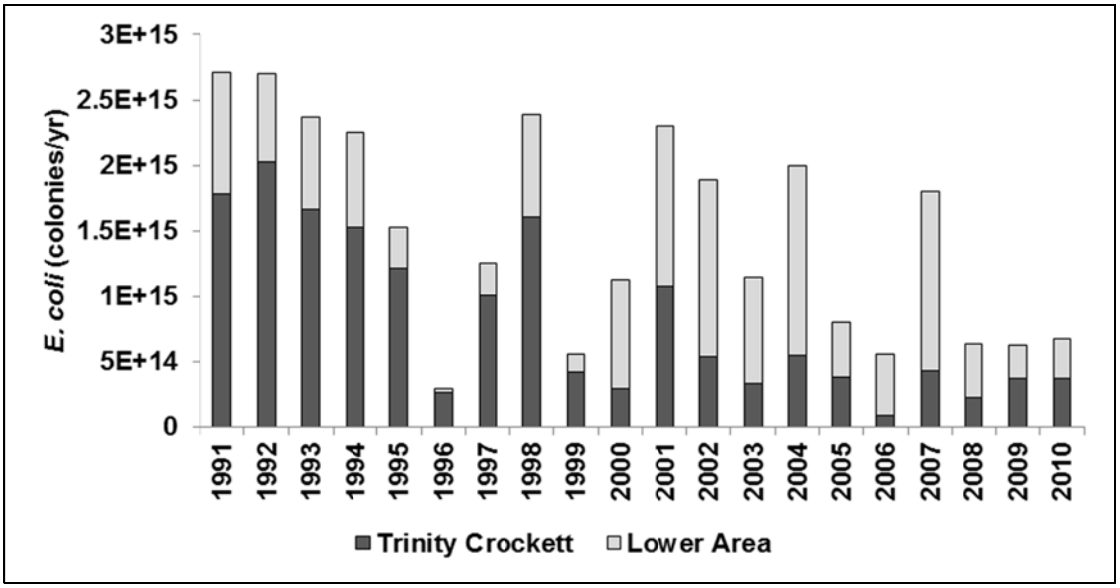

Figure 5-7 Annual estimated loading to Lake Livingston from the Trinity River near Crockett and the lower watershed area below Crockett of *E. coli.*

For nitrogen parameters (Figure 5-8), there appears to be a clear signature of a large amount of NH_3 loading from the lower portion of the watershed from about 1991 to 1995, which has tapered off to almost negligible amounts in 2006 through 2010. The loadings of NH_3 are relatively small compared to other nitrogen parameters, and the large amount of censored data, particularly for the Trinity River near Crockett makes these loading estimates somewhat suspect, but provides a "best" estimate of contributions based on available data. While NH_3 can provide nitrogen for algal growth, unless NH_3 is identified as a specific water quality issue, it is probably not worthwhile to focus more attention on refining loading estimates for this constituent. In 1991, the year with the largest estimated NH_3 loadings, NH_3 comprised only about 10 percent of the TKN loadings.

Based on estimated loadings for NO_3 and TKN, it appears that a larger portion of the organic than inorganic nitrogen loadings is contributed from the lower portion of the watershed nearer Lake Livingston (Figure 5-8). Only about 8 percent of the estimated nitrate loadings on average are contributed from the lower area, while about 25 percent of the estimated TKN loading is associated with the lower area.

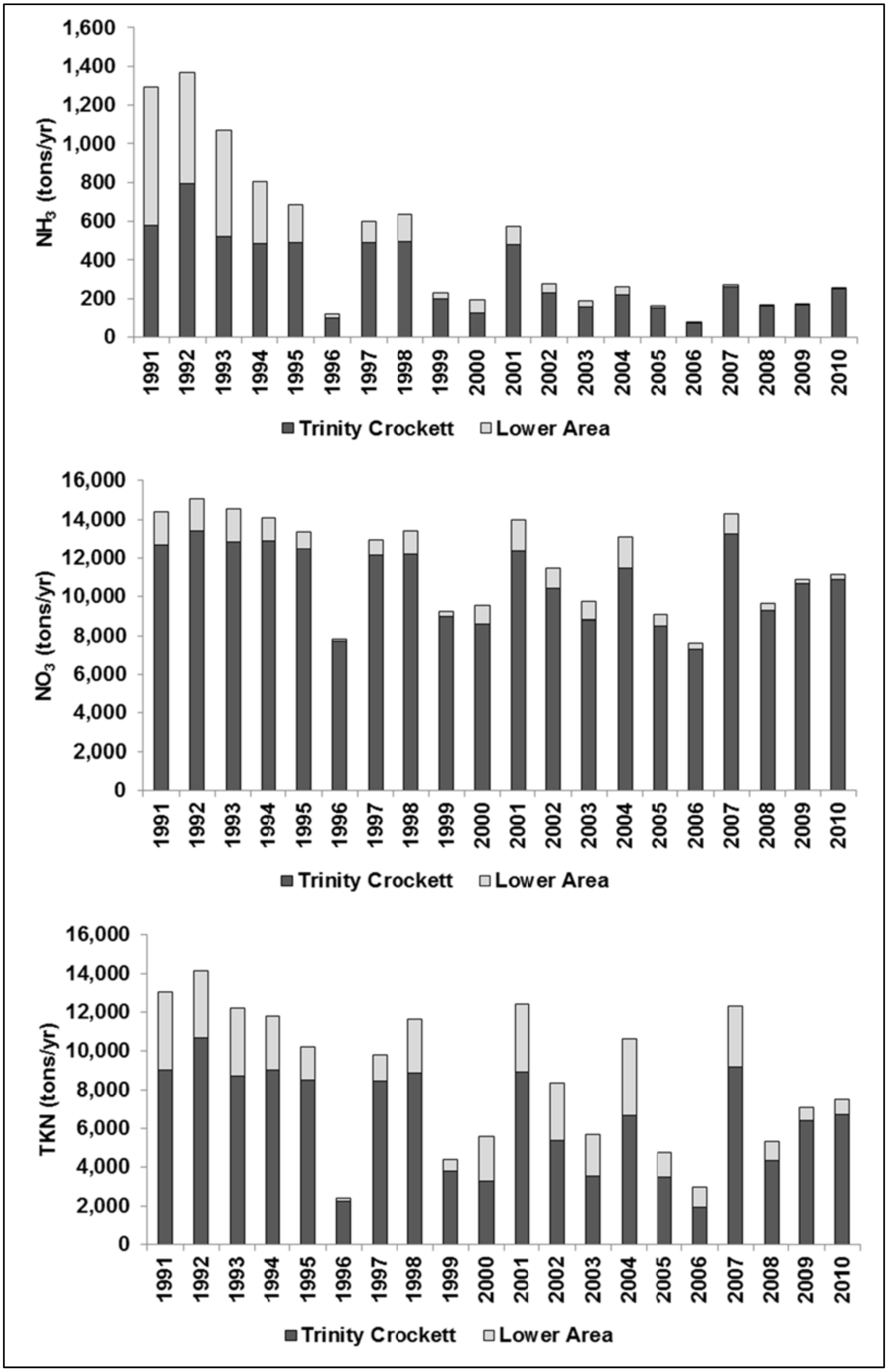

Figure 5-8 Annual estimated loading to Lake Livingston from the Trinity River near Crockett and the lower watershed area below Crockett of nitrogen

With regard to phosphorus, about 36 percent of estimated TP loadings are in the soluble form represented by OP. As mentioned earlier, about 88 percent of the estimated OP and TP contributions are associated with the Trinity River at Crocket and only 12 percent with the lower watershed area.

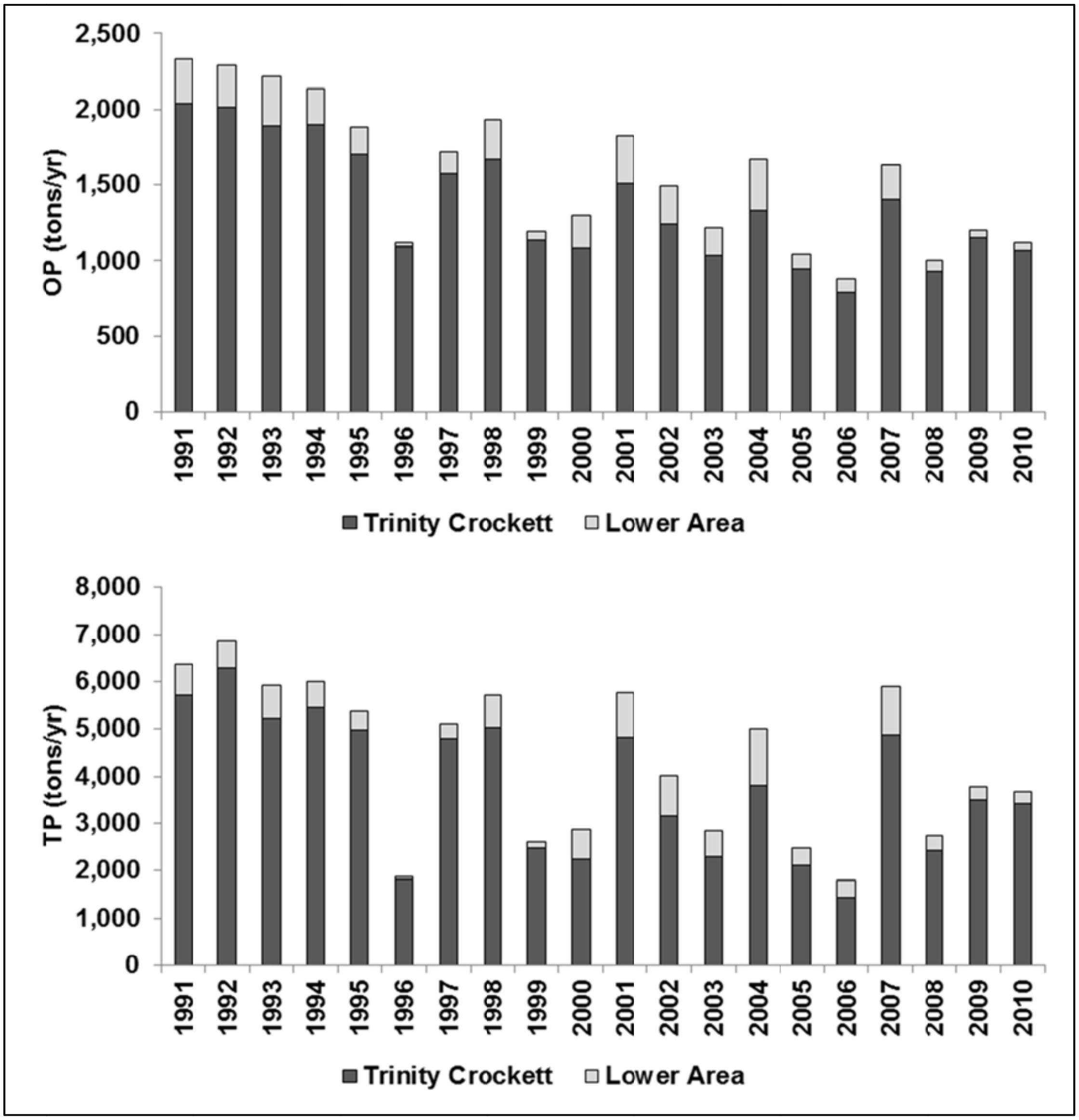

Figure 5-9 Annual estimated loading to Lake Livingston from the Trinity River near Crockett and the lower watershed area below Crockett of phosphorus

For TSS and SO_4 (Figures 5-10 and 5-11), loading patterns appeared very similar with regard to the source of contributions. About 89 percent of the estimated loadings came from the Trinity River near Crockett, while only 11 percent from the lower area closer to Lake Livingston.

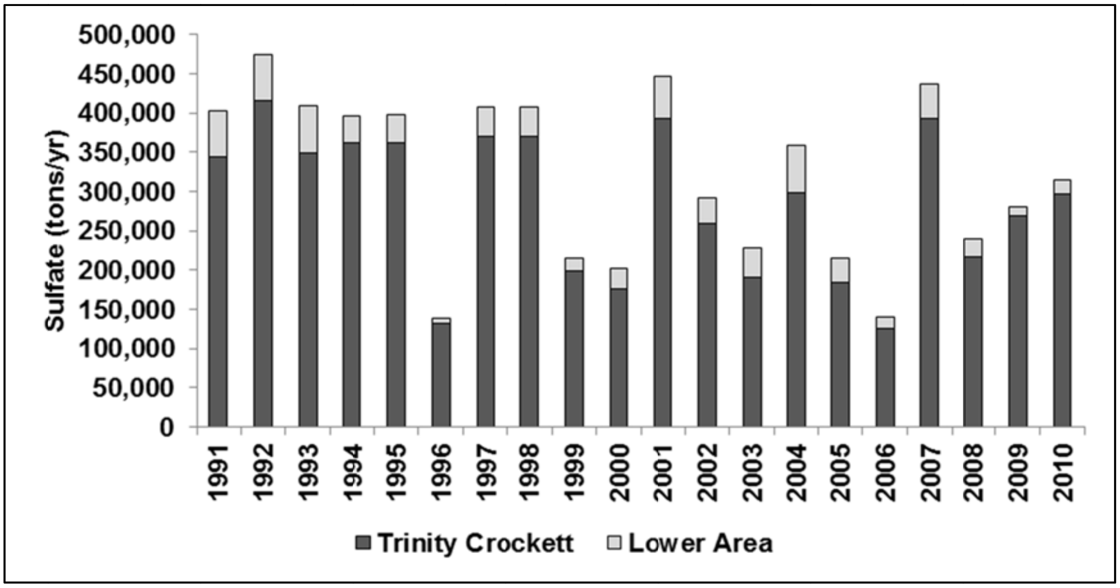

Figure 5-10 Annual estimated loading to Lake Livingston from the Trinity River near Crockett and the lower watershed area below Crockett of SO_4.

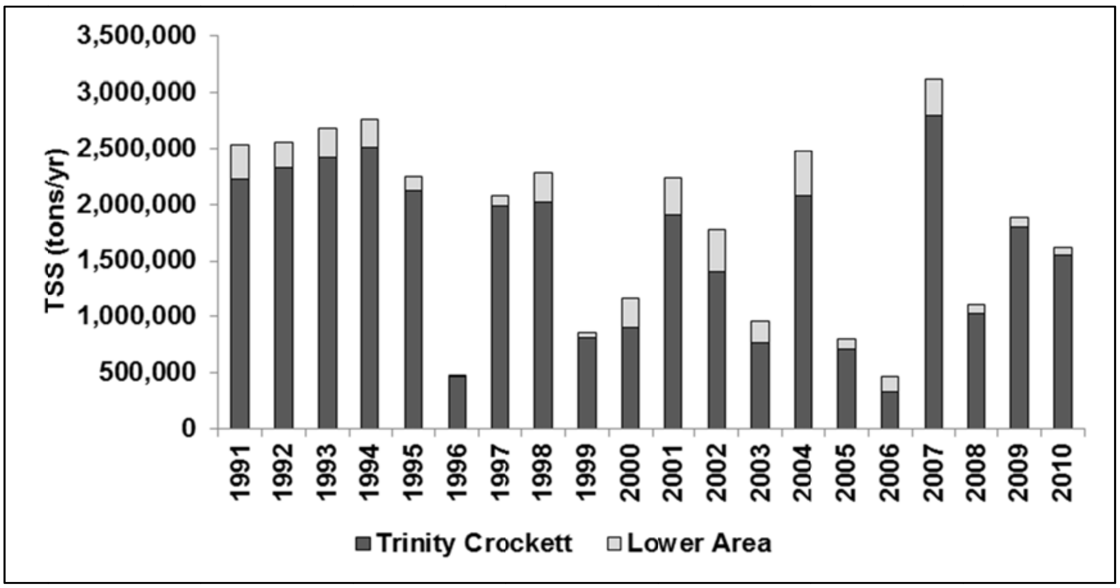

Figure 5-11 Annual estimated loading to Lake Livingston from the Trinity River near Crockett and the lower watershed area below Crockett of TSS.

Impacts of Flow and Time on Loading Estimates

The LOADEST regression models focus on flow and time as the primary factors impacting stream loadings. Because loading estimates provided by LOADEST are based on actual concentration and flow data, they can be used to investigate relationships of modeled concentrations to time and flow. These relationships of concentration to flow and to time may help provide some insight into loading sources and changes in concentration over time. Flow over time on the Trinity River near Crockett generally decreased (Figure 5-12), while daily flows along Bedias Creek showed no clear trend over time (Figure 5-13). The decreasing flows along the Trinity River greatly influenced the general decrease in loadings over time for most constituents when evaluating total loadings to Lake Livingston. In looking at very general directional trends, only estimated loadings of BOD_5 and Chl-a appeared to increase in association with decreasing flows for the Trinity near Crocket (Table 5-5). The increasing and decreasing trends noted for modeled concentrations (Table 5-5) closely matched trends noted for concentrations of the water quality data over a similar time presented in Tables 4-5 and 4-6.

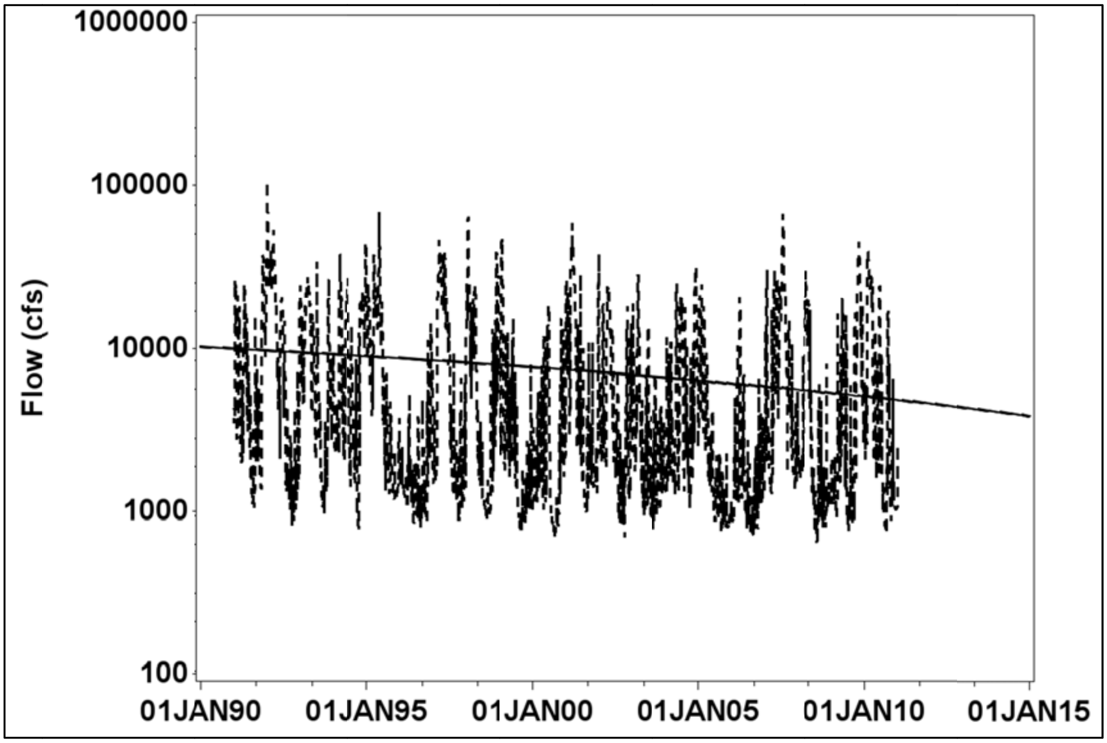

Figure 5-12 Daily flows 1991-2010 for the Trinity River near Crockett.

Table 5-5 General trend in LOADEST estimates of daily loadings and concentrations for 1991-2010. Direction of trend based on slope direction of simple linear regression line overlaid on plots of daily values. Null indicates no clear increasing or decreasing pattern.

Constituent	Bedias Creek		Trinity at Crockett	
	Load Over Time	Conc. Over Time	Load Over Time	Conc. Over Time
BOD_5	Null	Null	Increasing	Increasing
Chl-a	Null	Increasing	Increasing	Increasing
E. coli [a]	Increasing	Increasing	Decreasing	Decreasing
NH_3	Decreasing	Decreasing	Decreasing	Decreasing
NO_3	Decreasing	Decreasing	Decreasing	Increasing
OP	Decreasing	Decreasing	Decreasing	Null
TP	Null	Increasing	Decreasing	Null
SO_4	Null	Decreasing	Decreasing	Increasing
TKN	Decreasing	Decreasing	Decreasing	Null
TSS	Null	Null	Decreasing	Decreasing

a. Only fecal coliform values were available for the TCEQ stations 10702 and 10703 on Bedias Creek. These fecal coliform values were converted to E. coli by multiplying them by the ratio of geometric mean criterion for fecal coliform and *E. coli* set by TCEQ (126/200 = 0.63).

While flow is the primary driver in estimating loadings, concentration is the other important component. Back-calculated concentrations determined from daily loadings and then plotted over time showed a mix of general trends (Table 5-5). Modeled daily concentrations of BOD_5, Chl-a, NO_3 and SO_4 for the Trinity River near Crockett showed a general increasing pattern (Figure 5-14), while on Bedias Creek, increasing modeled concentrations were noted for Chl-a and TP (Figure 5-15). Decreasing concentrations over time were more commonly modeled with decreases in NH_3, NO_3, OP and TKN indicated for Bedias Creek (Figure 5-16), and decreases in *E. coli*, NH_3 and TSS indicated for the Trinity River near Crockett (Figure 5-17).

Because estimated loadings for all constituents except BOD_5 were based on regression models that considered factors other than just flow (see Tables 5-1 and 5-3), back-calculated concentrations generally showed a range of values when related solely to flow. Despite the broad scatter in these relationships for some constituents, relationships of modeled concentration with flow showed a few fairly distinct patterns. For the station on the Trinity River near Crockett, TSS and TKN showed a pattern of concentrations increasing steeply with flows up to about 15,000 cfs and then decreasing as flows further increased (Figure 5-18). The same pattern was still apparent for *E. coli*, but the range of concentrations was quite variable for a given flow. This large scatter in *E. coli* concentrations for a given flow indicates that the regression parameters associated with time have a large influence on the estimated *E. coli* loadings.

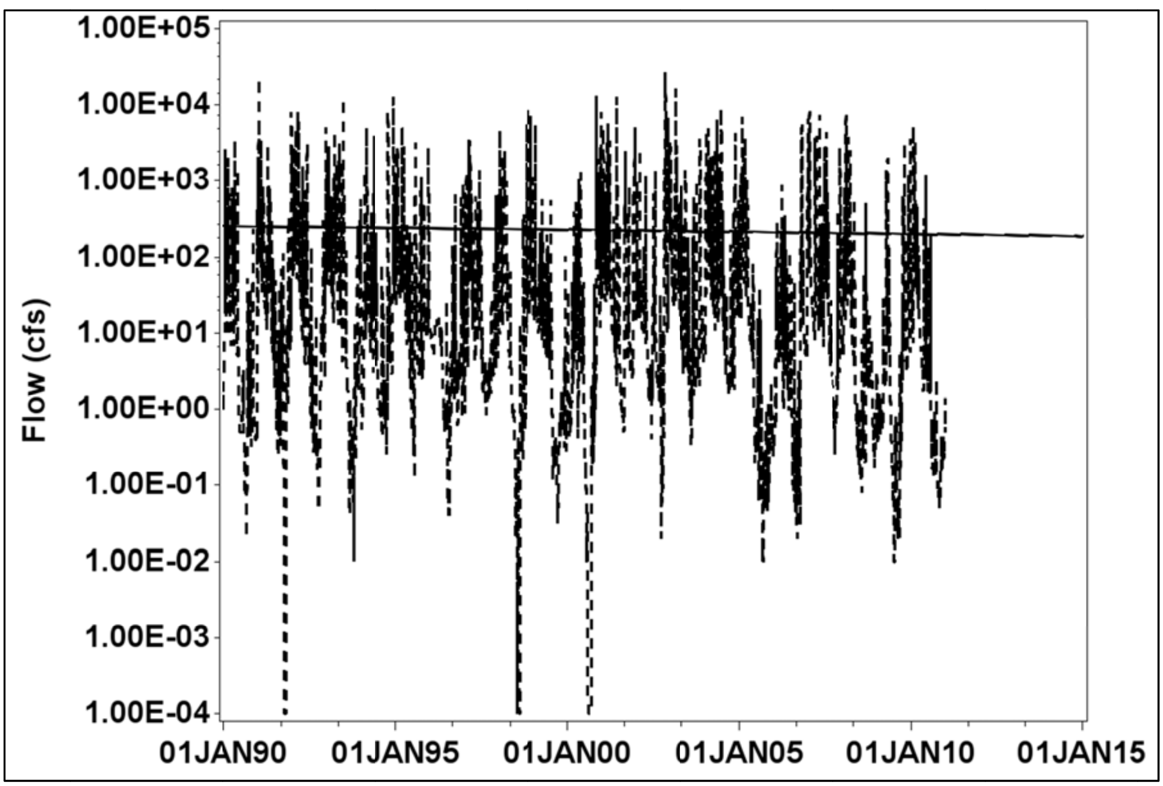

Figure 5-13 Daily flows 1991-2010 for Bedias Creek.

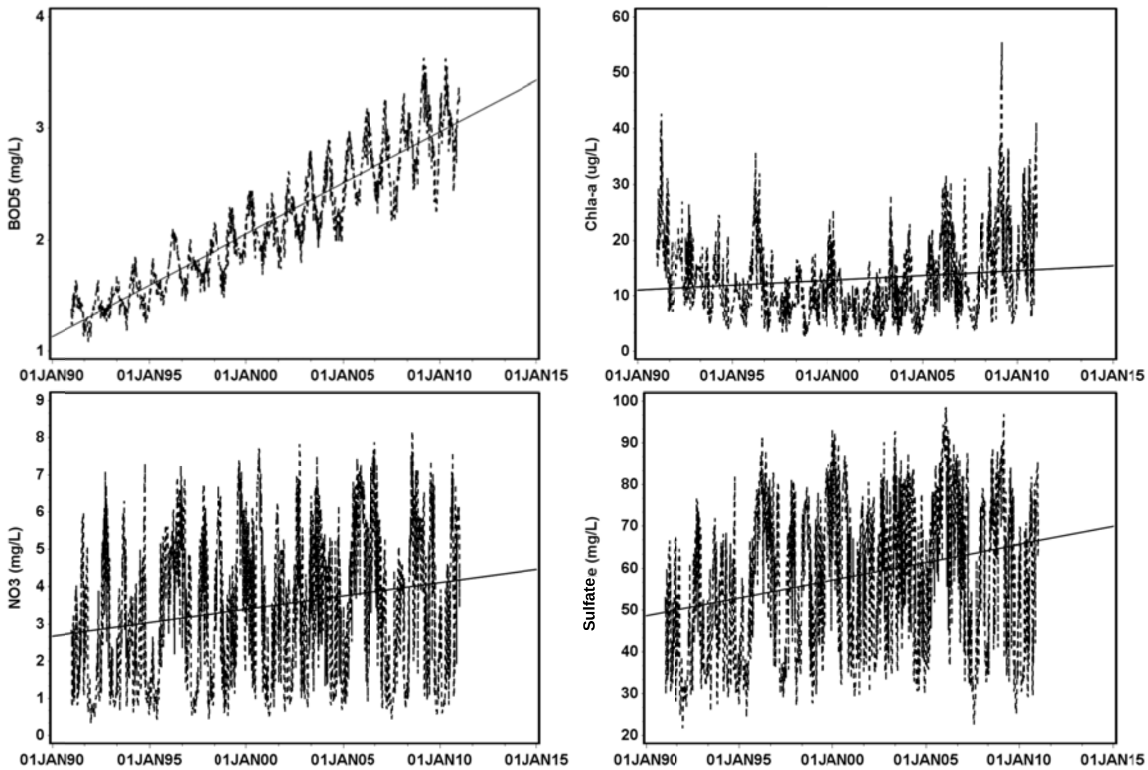

Figure 5-14 Daily modeled concentrations over time of BOD_5, Chl-a, NO_3 and SO_4 for the Trinity River near Crockett.

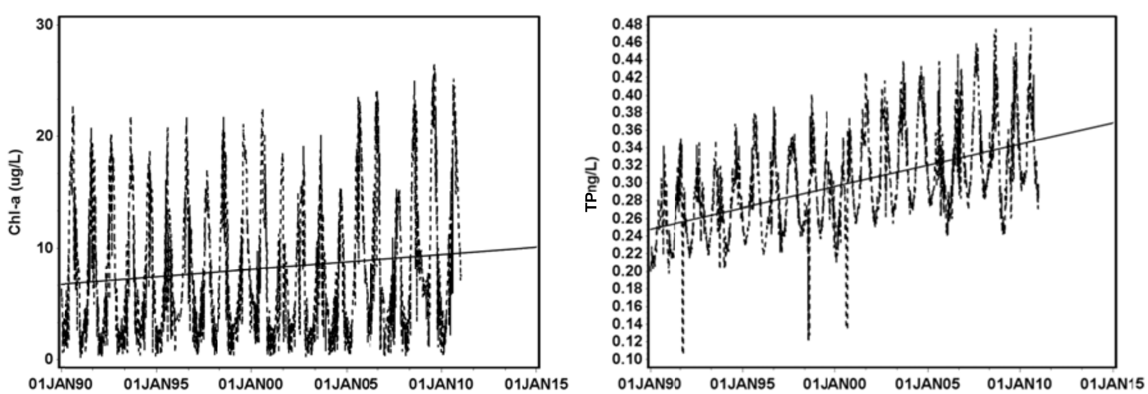

Figure 5-15 Daily modeled concentrations over time of Chl-a and TP for Bedias Creek.

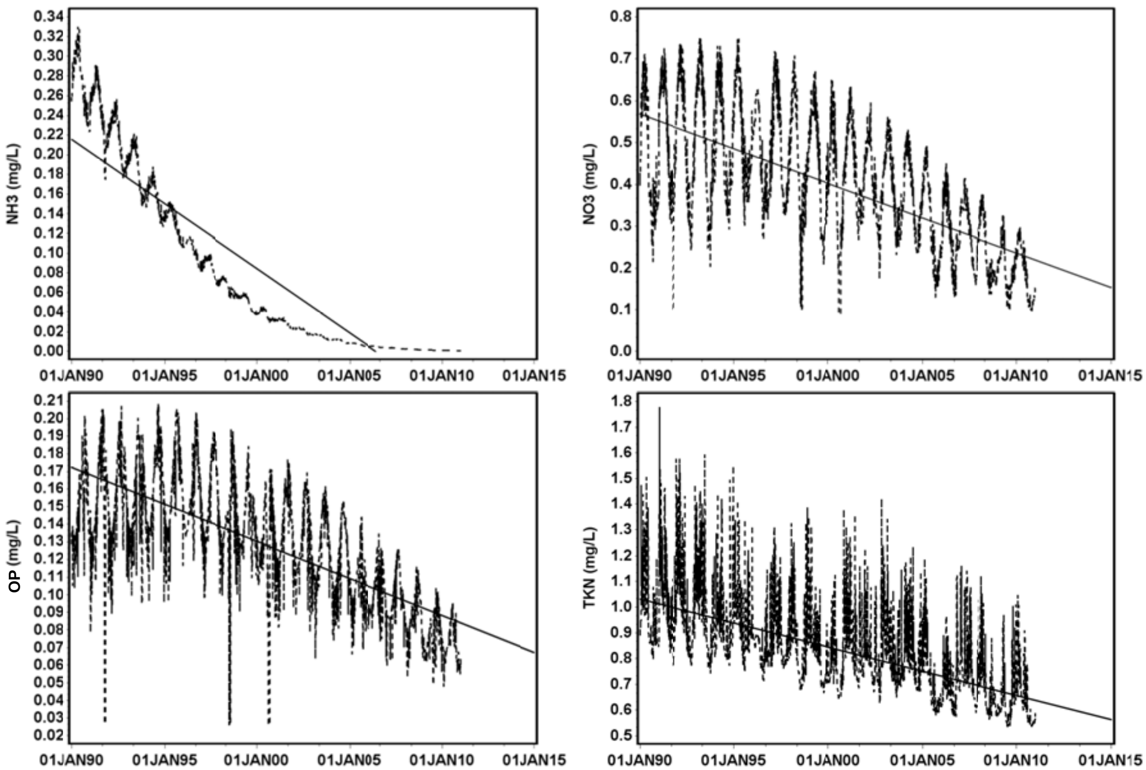

Figure 5-16 Daily modeled concentrations over time of NH_3, NO_3, OP and TKN for Bedias Creek.

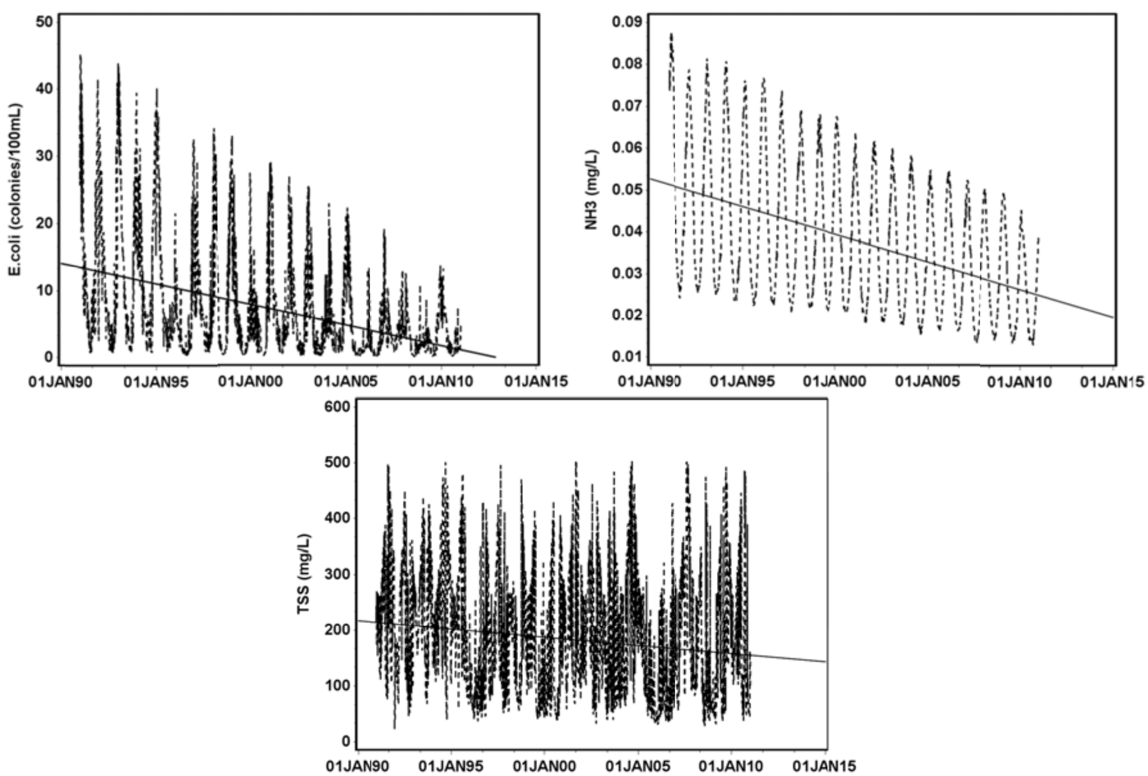

Figure 5-17 Daily modeled concentrations over time of *E. coli*, NH_3 and TSS for the Trinity River near Crockett.

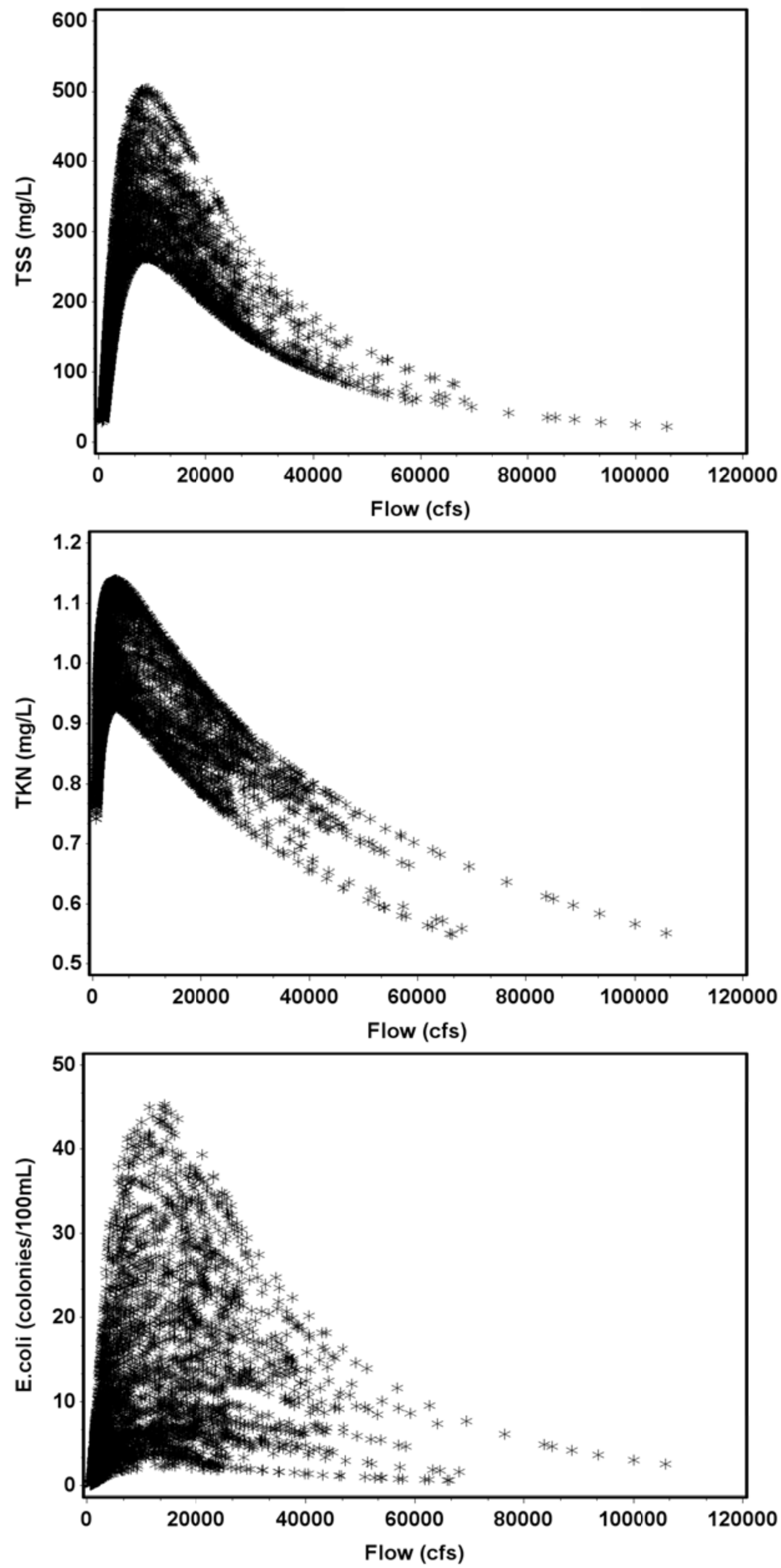

Figure 5-18 Daily flows compared to modeled concentrations of TSS, TKN and *E. coli* for the Trinity River near Crockett.

For NO_3, OP, TP and SO_4, a clear decreasing pattern of concentration with flow was modeled (Figure 5-19). This same general pattern occurred for Chl-a, but with an increasing concentration apparent after a large initial decrease with increasing flows. This general decreasing pattern of concentration with increasing flows is often associated with the dilution of point or baseflow sources with increasing flows from rainfall-runoff events. Because the Trinity River is a complex system, which also includes releases from reservoirs (Richland Chambers and Cedar Creek Reservoirs being closest to Lake Livingston), the normally anticipated responses of flow to concentration may not be as easily categorized into point and nonpoint source impacts. Of the other parameters (BOD_5 and NH_3) for the Trinity River at Crockett, the modeled pattern of concentration with flow was indistinct.

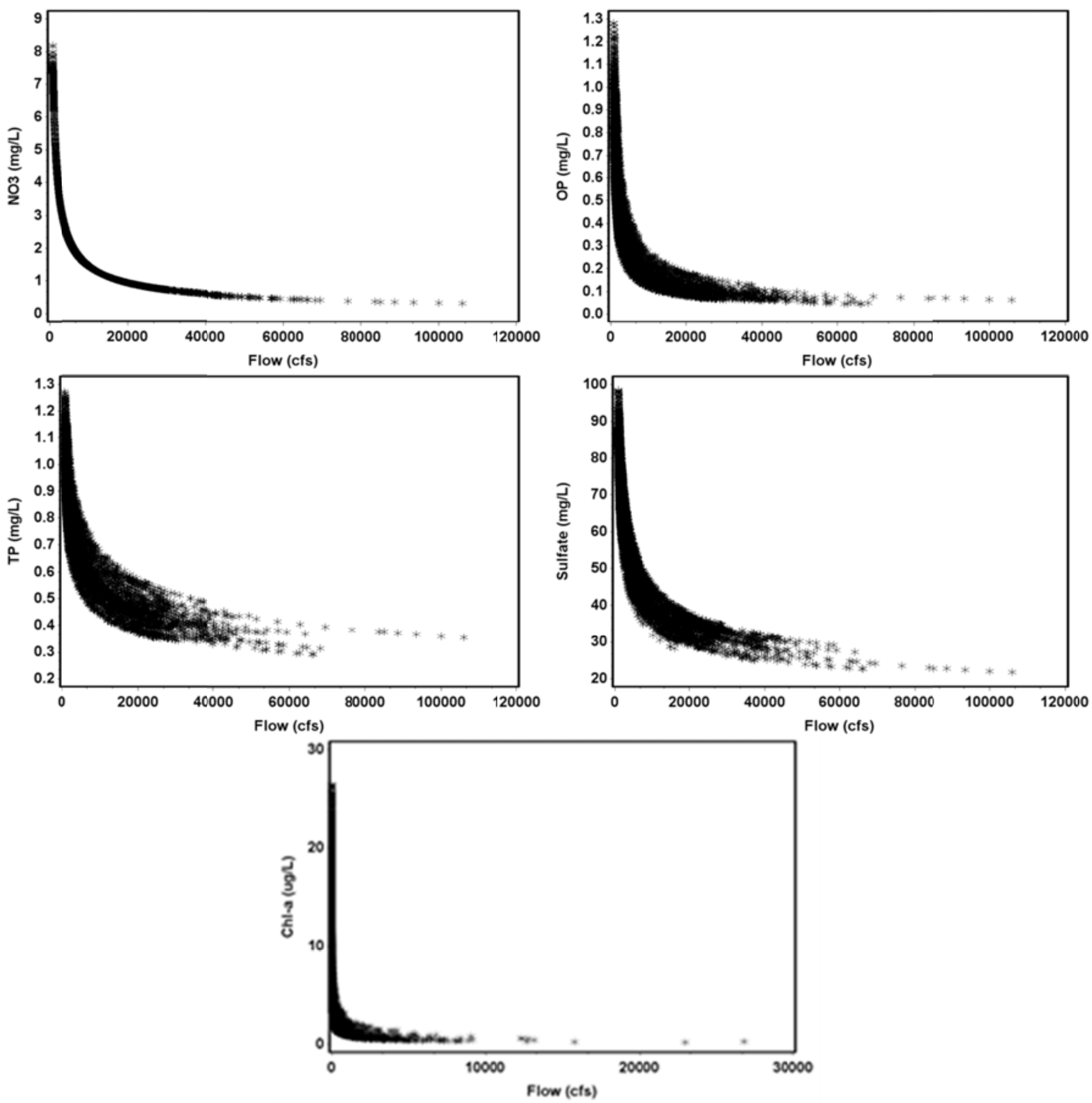

Figure 5-19 Daily flows compared to modeled concentrations of NO_3, OP, TP, SO_4 and Chl-a for the Trinity River at Crockett.

For Bedias Creek, a somewhat similar pattern of decreasing modeled concentrations with flow occurred for SO_4, Chl-a and BOD_5 (Figure 5-20). In contrast, Bedias Creek indicated an increasing pattern of modeled concentrations with increasing flow for *E. coli*, TKN, and TSS (Figure 5-21). A pattern of increasing concentrations with flow is often associated with predominately nonpoint source contributions. For TP, OP, NO_3 and NH_3, no clear pattern was indicated in the relationship of modeled concentrations with flow.

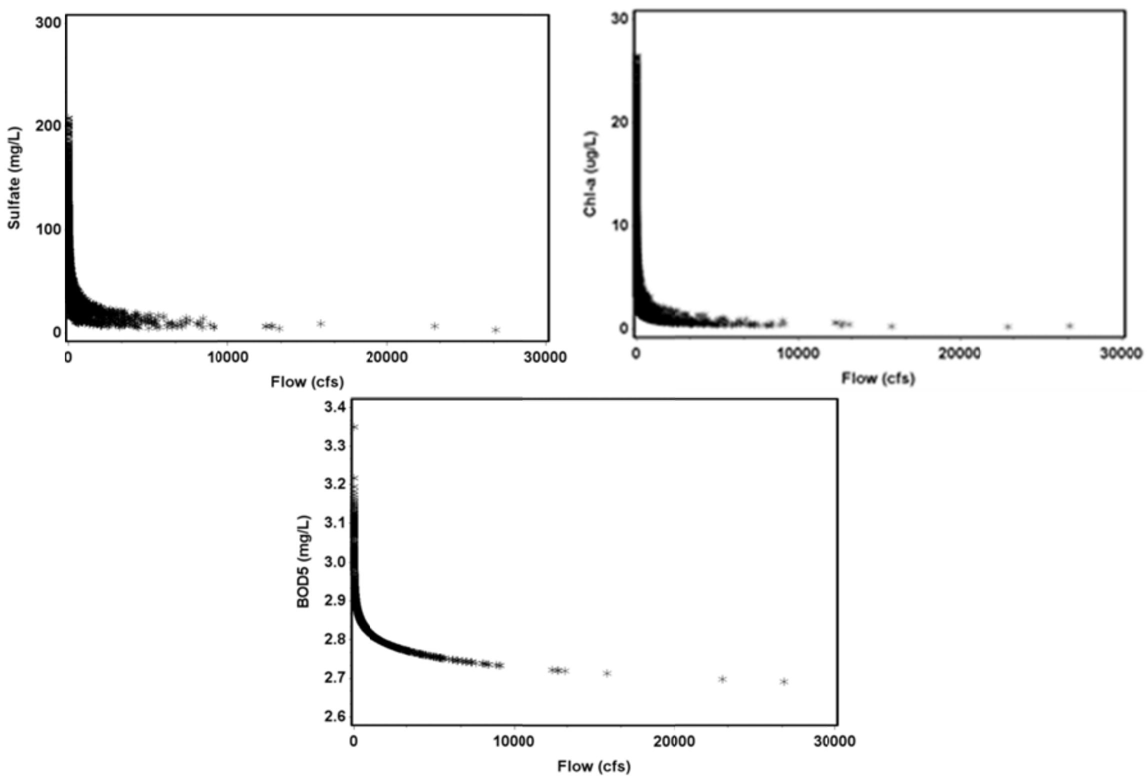

Figure 5-20 Daily flows compared to modeled concentrations of SO_4, Chl-a and BOD_5 for Bedias Creek.

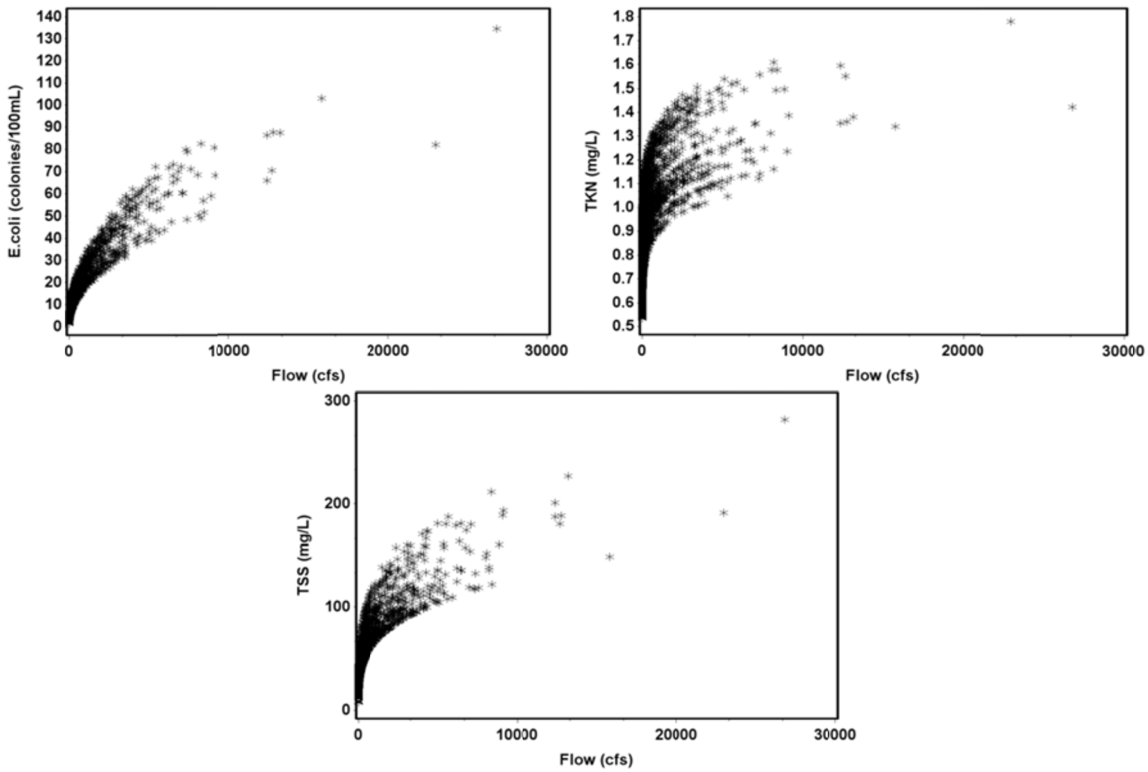

Figure 5-21 Daily flows compared to modeled concentrations of *E. coli*, TKN and TSS for Bedias Creek.

Summary and Discussion

Loadings to Lake Livingston were developed using the LOADEST FORTRAN program using flow data from the Trinity River at Crockett to represent the upper portion of the watershed and Bedias Creek to represent the lower portion of the watershed with paired water quality data for these locations. As anticipated based on flow, the largest portion of most constituent loadings to Lake Livingston were estimated to come from the Trinity River. Flow from the Trinity River at Crockett represented on average between 1991 and 2010 about 80 percent of the total flow into Lake Livingston. Based on LOADEST estimates 75 to 90 percent of most constituent loadings were associated with the Trinity River. There were two exceptions; one for *E. coli* and the other for Chl-a. For *E. coli*, loadings appeared to be more evenly split between the upper watershed area and the lower area nearer Lake Livingston. Of note, these loading results for *E. coli* for the lower area of the watershed were based on fecal coliform data that were converted based on a general ratio of *E. coli* to fecal coliform, so a watershed specific conversion factor might be considered in refining these results. For Chl-a, only about 3 percent of the total loading was estimated from the lower watershed area compared to the area represented above the Trinity River near Crockett.

Flows on the Trinity River near Crockett generally decreased over time, while daily flows along Bedias Creek showed no clear temporal trend. The decreasing flows along the Trinity River generally were related to decreased loadings over time for most constituents, although estimated increases in loadings appeared to occur for BOD_5 and Chl-a.

In looking at relationships of estimated concentrations versus flow, it appeared that point source contributions dominated at low flows along the Trinity River as shown with decreasing concentrations with increasing flow for parameters such as NO_3, OP, TP and SO_4 (Figure 5-19). For flows above about 10,000 cfs, releases from reservoirs upstream of the Trinity River at Crockett are suspected to complicate the interpretation of flows impacts on other constituents, such as Chl-a. Concentrations with flow for Bedias Creek indicate a more traditional nonpoint-source response with generally increasing concentrations with flow.

Chapter 6
Selection of Watershed and Lake Models

Watershed and Lake Modeling System

In addition to the overall characterization of Lake Livingston from hydrologic and water quality perspectives, an additional objective of this Phase I study was to recommend a modeling system that could be used to provide a mechanism to inform management decisions for Lake Livingston and its watershed. In general terms, mathematical models are analytical abstractions of the real world and as such they represent approximations of real world systems generated through mathematical equations incorporated into computer code operated on computer systems. In the context of watershed and lake management, mathematical models are computer based, simplified representations of landscape and water quality processes that govern the fate and transport of one or more pollutants.

Because of the differing physical and biochemical processes of watersheds and lakes, specific types of models are required that represent the unique characteristics of each system. Hence, a linked system of models is required for this application. A watershed model is needed to provide input information describing inflows and water quality loadings from the watershed of Lake Livingston and its drainage network of rivers and streams to a lake model.

While the individual watershed and lake components are discussed in more detail in subsequent sections of the report, succinctly this modeling system would consist of a watershed model of the area draining into Lake Livingston and a hydrodynamic/water quality model of the lake. Both models should have long-term predictive capabilities, meaning they are capable of simulating extended periods of time encompassing multi-years with a temporal resolution of at least daily, if not sub-daily, and spatial resolution allowing discernment of the variability within both the landscape and lake portions of the modeling system. The watershed-lake modeling system is shown schematically in Figure 6-1.

Watershed Model Selection

Application Requirements of Watershed Model

For overall project purposes, the watershed model will be used to simulate conditions in the Lake Livingston watershed and to provide input data of the streamflow and loadings of desired water quality constituents (e.g., dissolved oxygen, various forms of nitrogen and phosphorus, suspended sediment and organic matter) to the multi-dimensional lake model. In addition to loadings of water quality constituents, the model must be able to predict concentrations of these constituents within the Trinity River under a variety of flow conditions, including low flow. The watershed model should be able to include the discharge information from regulated (point) sources, such as municipal wastewater treatment plants. The model should also be able to evaluate the changes in water quality and flow from the voluntary implementation of selected agricultural management practices, e.g., nutrient management and grazing management.

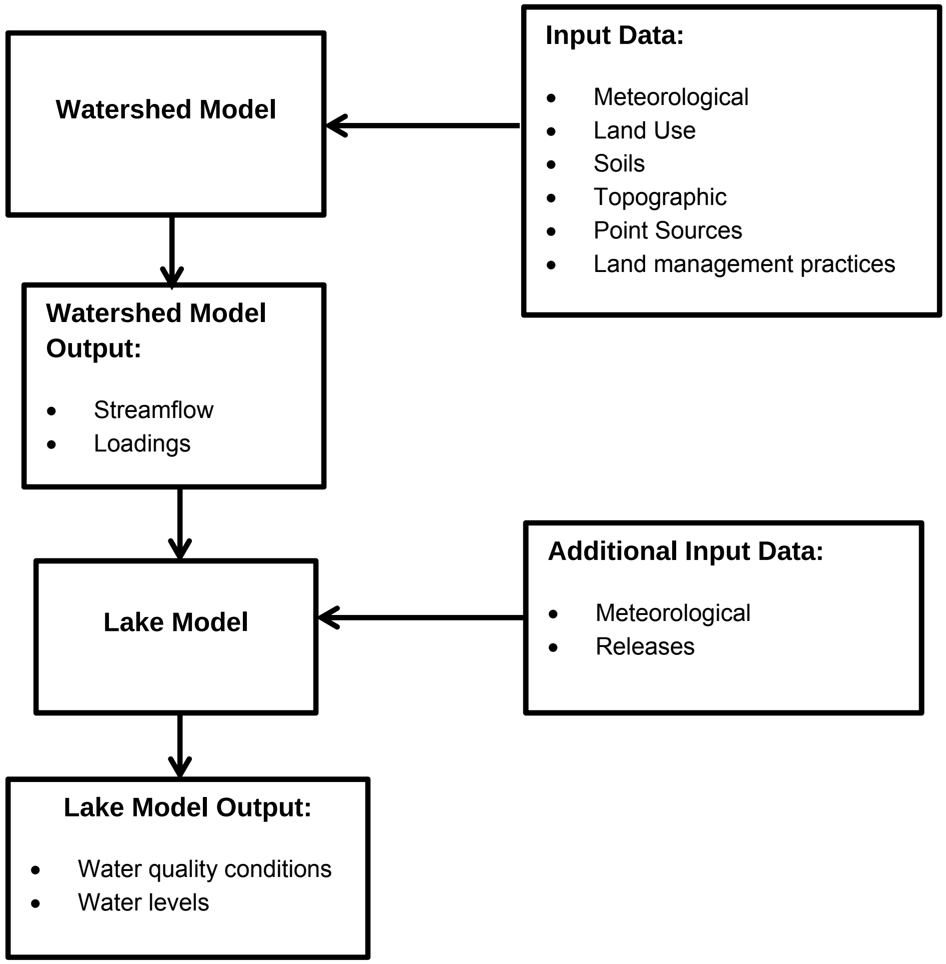

Figure 6-1 Schematic of Watershed-Lake Modeling System.

To accomplish the project purposes for the selected watershed model, it must be capable of predicting time series of flows and water quality constituents at selected locations within the Lake Livingston watershed. Typically, watershed models predict these time series at the outlets of subbasins into which the Lake Livingston watershed would be divided using GIS tools and databases. The number of subbasins is dictated in part by the degree of variation of land uses and land cover within the watershed, the stream network draining the watershed, and the spatial resolution desired for application of the model. Time series of meteorological data, such as air temperature and rainfall, become the driving input for the model to predict surface runoff, subsurface water movement and its interactions with surface flows, transport of water quality constituents in the soil and from the surface of the soil, and the fate of these constituents through the stream network into Lake Livingston. Often these types of models are operated for multiple years providing time series predictions on a sub-daily or daily basis.

Further, because of the very large watershed of Lake Livingston (16,600 square miles) and numerous major reservoirs in the watershed that significantly alter the natural streamflow and water quality, the drainage area to be included in this model would be constrained to roughly the watershed areas of Segments 0803 and 0804, excluding all areas above these segments including Richland Chambers Reservoir (Segment 0836). Thus the watershed area to be included in the model will be roughly 6,000 square miles.[2] The streamflow and water quality loadings for the excluded upper watershed area will need to be included in the model as one or more point sources. The selected watershed model must be readily adaptable to including the streamflow and water quality loadings from the excluded drainage area as input boundary conditions.

To further explain this concept of providing the streamflow and water quality loadings into the watershed model as a boundary condition, we will consider the situation of the upstream end of the watershed model being located on the Trinity River at the USGS gage at Trinity, Texas (State Highway 31 bridge crossing) as described above. This river location is also in proximity of two TCEQ monitoring stations (10921 and 10922). The daily streamflow record for this USGS gage, which exists from October 1964 to the present, provides the flow data needed as input at the upstream boundary of the watershed model. Statistical relationships using regression techniques of water quality constituents (e.g., total suspended solids and nitrates) to streamflow will need to be developed using the USGS streamflow record data and the water quality data from TCEQ stations 10921 and 10922. These statistical relationships for water quality constituents will be used to develop the daily water quality loadings that are associated with the daily streamflow at the upstream model boundary.

If appropriate statistical relationships cannot be developed for the relationships of water quality to flow at the Trinity River the State Highway 31 crossing, the watershed area modeled should be adjusted to accommodate a location where such relationships can be developed. For example, as presented in Chapter 5, good relationships were developed from the data available on the Trinity River at the State Highway 7 crossing near Crockett, a location nearer Lake Livingston.

Overview of Possible Watershed Models

Two models dominate the arena of watershed modeling – the Soil & Water Assessment Tool (SWAT) and the Hydraulic Simulation Program - FORTRAN (HSPF). Both models are supported in the USEPA BASINS (Better Assessment Science Integrating point & Nonpoint Sources), which is "a multi-purpose environmental analysis system that integrates a GIS, national watershed data, and state-of-the-art environmental assessment and modeling tools into one convenient package" (USEPA, 2007). Both SWAT and HSPF have been used extensively in Texas on Watershed Protection Plans and Total Maximum Daily Loads (TMDLs), and both models make use of extensive GIS databases, such as soils, land use, and digital elevation models, that are readily available for Texas, and which facilitate model development to a watershed and enhance accuracy of model predictions.

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[2] This approximate watershed area was estimated based on the total drainage area of Lake Livingston (16,600 sq. mi.) minus the drainage areas of both the USGS Trinity River at Trinidad gage (8,532 sq. mi) and Richland Chambers Reservoir (1,957 sq. mi.).

While both SWAT and HSPF have their similarities, there are notable differences in functionality. The following observations about both models are made based on the experience of TIAER staff and information in USEPA (2008). SWAT is generally applied at a one-day time step, meaning its temporal resolution is at that level, even though certain features within SWAT can allow computations to occur at a sub-day temporal resolution. HSPF, in contrast to SWAT, operates readily at temporal resolutions of less than one day or even subhourly. SWAT is generally considered stronger in agriculturally dominated watersheds, though it does have an urban component, which has been successfully applied in many watersheds. HSPF's strength is more in the urban environment, though it does have agricultural components. Both models can predict stormwater runoff and such water quality constituents transported by runoff as organic and inorganic forms of nitrogen and phosphorus, total suspended solids and even bacteria. HSPF would be considered the stronger of the two models when it comes to instream transport and kinetic process. SWAT would be considered stronger for applications in watersheds where runoff from agriculture and the rural landscapes is the dominate concern and where evaluation of alternative agricultural control practices is desired.

SWAT applications to a watershed require a moderate level of training and some knowledge of basic watershed and water quality principles, whereas HSPF is considered to require a higher level of expertise than SWAT to apply and requires generally more time and effort for calibration than SWAT. (Calibration is the process whereby values predicted by the model are compared to measured data and adjustments are made to various input parameters to the model to improve the similarity between predicted and measured datasets.) The calibration process, while especially time consuming with HSPF, is a tedious process with both models and is a necessary step in order to establish the ability of the model so simulate conditions in the watershed and to determine the level of confidence that can be placed in model predictions.

Both models can be linked to a lake model of Lake Livingston. The basic idea of the model linkage is that the watershed model is applied to simulate the area of the Lake Livingston watershed providing streamflow and water quality constituent loadings as input into the lake model. Further, both models allow point source input, which provides the capability to include as input the streamflow and water quality constituent loadings from the upstream watershed located above the domain of the model.

Watershed Model Selection

Both HSPF and SWAT have the needed capabilities to be an appropriate watershed model for application to the Lake Livingston watershed. Based on the rural, agricultural nature of the portion of the Lake Livingston watershed to be modeled (i.e., the drainage area of Segment 0803 and portions of Segment 0804) and the size of this watershed, SWAT is the preferred selection over HSPF. The typical daily time step in SWAT is adequate to capture the response of the watershed to rainfall runoff events, which are typically multiple days in duration for a watershed of this large size. Also, the greater abilities of SWAT over HSPF to simulate agricultural land uses and to mechanistically simulate many agricultural best management practices provide additional advantages of SWAT.

If the main purposes of the watershed model change from simulating the agricultural landscape and associated best management practices to an emphasis on simulating instream dissolved

oxygen and instream kinetics operating on water quality constituents, then HSPF would require more serious consideration, as those areas are not strengths of SWAT. The requirement of the selected model to be able to simulate instream nutrient concentrations under both low and high flow regimes is more of a strength of HSPF than SWAT, but SWAT has been successfully applied to predict instream concentrations, for example, for the North Bosque River phosphorus total maximum daily load (Houser and Hauck, 2010). Finally, SWAT is generally considered an easier model to operate than HSPF and typically requires less effort to be made operational.
In summary, based on the present application focus of the desired model of the Lake Livingston watershed, SWAT is recommended over HSPF.

Lake Model Selection

Application Requirements of Lake Model

From a water quality perspective based on the TCEQ 2010 Integrated Report (TCEQ, 2010b), Lake Livingston experiences impairment of its designated general use due to elevated levels of sulfates and pH. The same report indicates concerns in support of the general use due to elevated levels of some nutrient forms and chlorophyll-a for portions of Lake Livingston. Some analyses of Lake Livingston water quality data link elevated pH values to the summer season and phytoplankton photosynthesis activity, which uses up carbon dioxide and, as a weak acid, the uptake of carbon dioxide from lake water results in pH increase (Pendergrass and Hauck, 2008).

The lake model selected for Lake Livingston should have capabilities to simulate water quality and hydrodynamic conditions in at least two dimensions within the lake – in the vertical direction from surface to bottom depths and longitudinally along the downstream-to-upstream axis of the lake. If small cove areas of the lake become a major focus, then a three-dimensional model may be required that allows simulation in the lateral direction across the lake.

Regarding water quality, the model needs capabilities to predict water temperature and vertical temperature/density stratification in the deeper parts of the lake during the warm season. The model should have the capability to simulate dissolved oxygen and the major influences on dissolved oxygen from surface reaeration, dissolved and suspended oxygen demanding substances, sediment oxygen demand, and photosynthesis/respiration of phytoplankton. Various organic and inorganic forms of nitrogen and phosphorus and their linkage to growth rates for phytoplankton is another critical component of the desired lake model.

Another important need of the lake model is to have predictive capabilities regarding nitrate concentrations, especially in the upper reaches of the lake, where under low-flow conditions in the Trinity River, high nitrate levels can occur at the City of Huntsville water supply intake.

Finally, model capabilities to simulate pH and conservative substances, such as total dissolved solids, are important. Because occurrences of elevated SO_4 concentrations are a concern in Lake Livingston, model capabilities to simulate this ion would be beneficial; however, this constituent is not typically included in available lake models.

Overview of Possible Lake Models

Two models dominate the arena of multi-dimensional lake modeling – CE-QUAL-W2 and EFDC (Environmental Fluid Dynamics Code). Though several predecessor codes existed, the CE-QUAL-W2 model was developed by the U.S. Army Engineers Waterways Experiment Station with version 1 released in 1986. Much of the present model development occurs at Portland State University in Oregon and the present version is 3.6. Version 3.5 of CE-QUAL-W2 was applied by PBS&J to Lake Livingston in the evaluation of the proposed hydroelectric project on the lake (PBS&J, 2008). This model is public domain and can be readily obtained from various websites. This model provides for two-dimensional (vertical and longitudinal) characterization of lakes, reservoirs, and tidal systems with an inherent assumption of insignificant variation in the lateral direction. The model may be employed in a quasi three-dimensional manner to include such water bodies as large coves. In addition to capabilities to predict hydrodynamics (e.g., water elevation and lake circulation) and water temperature, the model can simulate pH, dissolved oxygen, phytoplankton, various organic and inorganic forms of nutrients (e.g., ammonia and nitrates), oxygen demanding organic matter, and sediment-water exchange processes.

The EFDC model was developed in the early 1990s at the Virginia Institute of Marine Science. The version of the model supported by the USEPA is a state-of-the-art three dimensional model that can be applied to lake and reservoir systems as well as estuarine systems. EFDC-Hydro, the hydrodynamic version of the model, is public domain and can be obtained from an USEPA website. The water quality component of EFDC is proprietary and not supported by the USEPA. For applications requiring water quality considerations, EFDC-Hydro is designed to provide output to the transport input fields needed to drive such water quality models as WASP (Water Quality Analysis Simulation Program), which is a public domain model developed in the 1980s that is readily available from USEPA. WASP is a multi-dimensional water quality model, which as indicated immediately above, must receive transport information (e.g., flow information) from a hydrodynamic model such as EFDC. WASP contains extensive capabilities for simulating water quality constituents and contains similar features to the water quality component of CE-QUAL-W2 that have already been mentioned.

Evaluation of Existing CE-QUAL-W2 Lake Livingston Model

The CE-QUAL-W2 model was recently set up for Lake Livingston in order to make certain evaluations of the proposed hydroelectric project on the lake (PBS&J, 2008). The following information is taken from PBS&J (2008). The focus of the model application was on the main body of the lake in front of the Lake Livingston Dam, the stilling basin between the dam and the weir dam, and the proposed tailrace area downstream of the weir dam. Each of these three water bodies was divided into longitudinal segments and each of these segments was divided into vertical layers 1-meter (3.28 feet) thick. A plan view of the CE-QUAL-W2 segmentation of Lake Livingston is provided in Figure 6-2. The model segmentation includes 16 longitudinal segment; 12 segments comprise the main length of the lake (Segments 2-13) and 2 each for the eastern cove area where Kickapoo Creek enters the lake (Segments 20 & 21) and a northern cover area where White Rock and Caney Creeks enter the lake (Segments (16 & 17). Meteorological input data required by the model was obtained for the Huntsville Municipal Airport weather station and recorded lake releases by TRA were used as both inflow and outflow to the model. Inflow loadings required by the model were determined from streamflow and water quality data for the Trinity River at Crockett.

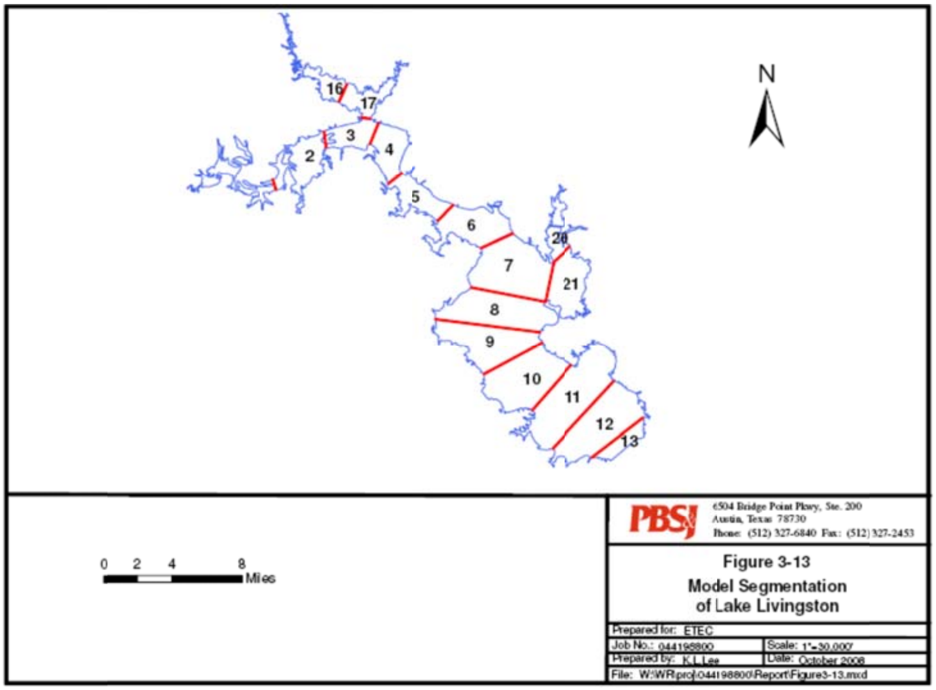

Figure 6-2 Plan view of CE-QUAL-W2 segmentation of Lake Livingston (Source: PBS&J, 2008)

The following critique is provided of the existing CE-QUAL-W2 model of Lake Livingston based on the information in PSB&J (2008), including Appendix E of the report.

1. Operated with CE-QUAL-W2 Version 3.5: Version 3.6 of CE-QUAL-W2 was released February 10, 2012. Based on notes on the release of Version 3.6, the data files for Version 3.5 are reported to be compatible with and be able to be run on the new version. Further, while some enhancements have occurred with the most recent version, there appear to be no substantive changes between versions. The reported backwards compatibility between the present model version (3.6) and the version (3.5) used previously for evaluating proposed hydroelectric development of Lake Livingston minimizes concerns over any issues associated with version change.
2. Segmentation: While the horizontal (or plan view) segmentation of the lake is likely adequate for many applications and needs, it is inadequate for addressing the concern regarding nitrate concentrations at the City of Huntsville water intake in the upper part of the lake. The existing segmentation does not include the upper most reaches of the lake where the Huntsville water intake is located.
3. Constant Level Assumption: The model was operated assuming that inflows equal outflows, thus forcing the model to behave with a constant lake volume and elevation. Because the lake is, in fact, operated to release what is inflowing, this assumption is valid for many situations. Limitations of this assumption could occur under special situations that could be of interest, such as the forced lowering of the lake after damage to the dam during Hurricane Rita, drought situations such as occurred in 2011, and perhaps even

environmental flow releases. While the constant lake level assumption was acceptable for the evaluations needed for the proposed hydroelectric project, this assumption unnecessarily limits model application. Calibration of the model to better account for fluctuations in lake level at a monthly temporal scale would be beneficial to broadening model applicability.

4. Water Quality Calibration: Based on what could be discerned from PSB&J (2008), the Lake Livingston model was only calibrated against water quality data collected near the dam, which provided adequate calibration for the needs of the hydroelectric study. It is envisioned, however, that for many model applications longitudinal variations in water quality within the lake will be of interest and perhaps even the focus. More exhaustive calibration against water quality data collected at stations along the longitudinal axis of the lake, and ideally within the two coves included in the model segmentation, would provide the opportunity for developing a more robust model with greater flexibility in its application.
5. Linkage to Watershed Model: To achieve the purposes of assessing the hydroelectric project, it was unnecessary to link the Lake Livingston model to a watershed model. Such a linkage, however, would enhance the application of the lake model regarding the ability to access how changes in the watershed impact lake water quality. Any type of watershed planning tool for Lake Livingston should seriously consider the linkage of an appropriate watershed model to the lake model.

In summary the present CE-QUAL-W2 model of Lake Livingston, while adequate for making certain needed assessments of the proposed hydroelectric project, provides a good starting point but is inadequate as part of a watershed management tool. Beneficial enhancements toward a goal of achieving a more complete lake model include expanding the segmentation to include the uppermost reaches of the lake, allowing dynamic water level variation by not forcing inflows to equal releases, performing additional water quality calibration to gain confidence in the ability of the model to reproduce the longitudinal water quality gradients in the lake and its major coves, and developing linkage to a watershed model.

Lake Livingston Model Selection

The CE-QUAL-W2 model is recommended as the preferred hydrodynamic/water quality model for Lake Livingston over a linked EFDC-WASP modeling system, though both approaches have the potential of providing an excellent tool with similar capabilities. While it is reported to be an easy interface between EFDC output as data for input into WASP, the additional linkage for this system results in a preference for the single CE-QUAL-W2 model over a two-model system of the lake. The other advantage is that CE-QUAL-W2 has previously been applied to Lake Livingston, and though applied for a different purpose (i.e., the evaluation of the proposed hydroelectric project), some of the information and files used in the previous model application would likely be applicable in applying the model to meet the current project objectives. If applications of the selected model are envisioned to require spatial resolution of water quality changes in the lateral direction across the lake, such as in small coves along the shoreline, then the three-dimensional capabilities of the EFDC-WASP modeling system are preferred. CE-QUAL-W2, while allowing two-dimensional representation of the lake, cannot provide three-dimensional capabilities, except in a quasi three-dimensional manner for water bodies, such as large coves.

Summary

The selection of the components for a watershed-lake modeling system is an objective of the Phase I of the Lake Livingston Watershed Study. While the viable options for a watershed model and for a hydrodynamic/water quality lake model are rather limited, the options are good proven models. For the watershed model component, the SWAT model is given preference over HSPF, because of easier application and stronger capabilities in the arena of agricultural and rural landscapes. For the lake model, CE-QUAL-W2 is preferred over a combined EFDC-WASP hydrodynamic/water quality modeling system. For the lake, CE-QUAL-W2 is preferred because it has previously been applied to Lake Livingston and has a less complicated input interface than EFDC-WASP as a single rather than two-phase model. While CE-QUAL-W2 is limited to the vertical and longitudinal dimensions, as opposed to fully three-dimensional representation available with EFDC-WASP, it is fully anticipated that the major water quality variations in Lake Livingston occur in these two dimensions.

Chapter 7
Conclusions and Recommendations

Potential Water Quality Threats to Lake Livingston

Elevated nutrients are currently the major threat to water quality within Lake Livingston, resulting in more frequent algal blooms than would occur under conditions of less loadings of nutrients. The immediate effect of these algal blooms with regulatory implications is seasonally elevated pH levels, which have resulted in portions of the lake being listed for high pH on the State's 303(d) list. Further symptoms of the elevated nutrients are that, with the exception of NH_3, monitored nutrient forms and Chl-a exceed TCEQ screening levels in many areas of Lake Livingston resulting in what TCEQ considers water quality "concerns." The LOADEST analysis indicated that nutrient loadings to Lake Livingston predominately originate from the Trinity River and that higher nutrient concentrations occur in the river under low-flow conditions. Concentration increases with decreasing flow reflect dominance of point source contributions. The strong upstream to downstream decreases in nutrient concentrations along the Trinity River implicate the DFW area as a major source of nutrients entering the lake.

A related facet of the elevated nutrients is the episodic occurrence of elevated NO_3 levels at the City of Huntsville water intake in the upper portion of Lake Livingston. The analyses in this report support temporal trends of increasing NO_{23} in the Trinity River, though a more limited NO_3 dataset would not support this trend. Other evidence in this report, however, would support a reason for continued awareness of conditions conducive to increased NO_3 levels within the upper reaches of Lake Livingston. This evidence includes the significant increase experienced in the annual minimum 7-day average flows along the Trinity River, which is an indication of increasing amounts of WWTF effluent entering the Trinity River and its tributaries, and the LOADEST analysis of concentrations, which showed a gradual increase in NO_3 concentrations over time for the Trinity River near Crockett.

Based on TCEQ assessment and the existing general use criterion for SO_4, Lake Livingston has a recent history since the year 2006 of being on the State's 303(d) list for elevated SO_4. The assessment for SO_4 is conducted using a combined dataset for the entire lake, which has resulted in every AU within the lake being included on the list. The SO_4 data, however, indicate the highest values occur in the upstream portion of the lake with values gradually decreasing to levels predominately below the criterion of 50 mg/L at stations nearest the dam. It should be noted that the effective SO_4 criterion for the lake is 50 mg/L; however, the 2010 Texas Surface Water Quality Standards contains a SO_4 criterion of 60 mg/L. If this higher criterion is approved by the U.S. Environmental Protection Agency, Lake Livingston data will indicate non-impairment for SO_4.

Any analysis to determine potential water quality threats from tributaries directly entering coves of Lake Livingston is largely precluded by data limitations. The scarcity of streamflow and water quality data for tributaries surrounding Lake Livingston prevents meaningful analysis of loadings to the lake from these individual tributaries. Likewise, a general lack of water quality data in coves of the lake, while understandable given the large size of the lake, further prevents analysis of local impacts. Data are also scarce on any impacts from the numerous WWTFs within the immediate vicinity of the lake. These facilities are, however, all small. Their contributions of nutrients must be considered minor compared to loadings of nutrients entering from the Trinity River and impacts of their discharges, if any, isolated to small coves along the Lake Livingston shoreline.

Evaluation of Existing Monitoring Network

The temporal and spatial analyses conducted for this Phase I study have afforded the opportunity to evaluate the existing monitoring network for the Trinity River, creeks and streams that are direct tributaries to the lake, and Lake Livingston. The findings of this evaluation are summarized below.

Trinity River

The upper reaches of Segment 0805 and the lower reaches of Segment 0804 are the best monitored sections of the Trinity River between Dallas and Lake Livingston (Figures 4-1 – 4-2; Table 3-2). Since 2005, the only monitoring stations that have been sampled with some intensity are Stations 10935 (AU 0805_03), 10925 (AU 0805_02) and 13690 (AU 0804_01). Stations 10937 (AU 0805_04), 10922 (AU 0804_07) and 10919 (AU 0804_04) have been sampled regularly but less intensively. Station 10919 is ideally collocated with USGS streamflow gage 08065000 (Trinity River near Oakwood), which has a robust record of flow data (Table 3-5), and it is the station with the most water quality data in the last 10 years that is closest to the flow emanating from Richland-Chambers and Cedar Creek Reservoirs. Yet Station 10919 has relatively few records since 2008.

The 15 key parameters are generally well represented in the monitoring of the warm-season months of May – August and of the cool-season months of February and November (Table 7-1). Exceptions are NO_3, TSS, BOD_5 and Alky, all of which were sampled less frequently than the other parameters and generally during warm rather than cool season months. Sampling of BOD_5 is weak throughout the year in Trinity River stations, but October – December showed fewer samples of BOD_5 than any other parameter for that period of the year (Table 7-1). The coldest months, December – January are data-poor along with the transitional months of March – April and September – October. As most water quality issues for Lake Livingston appear to be related to the warm season, the paucity of cool season samples may be less important to address than the spatial distribution of sampling stations. The uppermost stations of Lake Livingston (10917 and 10914) showed the highest annual NO_3 values during October and November (Table 4-11), yet these months had the fewest NO_3 samples for the Trinity River stations (Table 7-1). Increased NO_3 sampling in the lower Trinity River above Lake Livingston (e.g., Station 13690) during the cool season may be warranted to enable more rigorous analysis of patterns leading to higher NO_3 during fall months.

Table 7-1 Distribution of samples by month for each of the 15 key parameters, Trinity River surface samples, 1991 – 2011. Shading is relative to each month within each parameter row; the 10 stations used are identical to those in Table 3-2

Trinity River													
Parameter	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**TOTAL**
NH_3	89	118	94	95	109	98	113	117	88	75	106	76	1178
TKN	69	94	56	64	81	80	74	72	61	55	93	59	858
NO_3	22	18	24	21	22	25	23	37	21	18	16	22	269
NO_{23}	76	105	87	93	102	96	109	110	75	65	97	70	1085
OP	87	119	91	96	106	107	114	119	87	74	100	75	1175
TP	72	100	73	80	99	81	84	96	72	63	87	68	975
Chl-a	50	82	50	54	71	55	57	76	60	48	72	49	724
SO_4	56	77	71	73	85	83	82	90	70	45	67	56	855
E. coli	48	68	47	57	66	48	56	66	40	44	65	40	645
TSS	33	34	30	35	34	35	45	33	37	38	38	31	423
BOD_5	16	16	21	26	19	24	30	26	17	4	13	6	218
Fcoli	19	21	14	22	23	22	16	16	15	13	16	15	212
pH	96	126	99	115	135	123	129	134	106	84	113	84	1344
Alky	32	34	29	33	35	36	36	34	34	30	31	29	393
WaterT	96	129	102	115	137	125	129	139	108	84	113	85	1362
TOTAL	861	1141	888	979	1124	1038	1097	1165	891	740	1027	765	***11716***

Tributaries

The vast majority of intensive sampling of Lake Livingston tributaries occurred between 1972 and 1986 (Table 3-3). Since 1998, Bedias, White Rock and Harmon Creeks have only been sampled one or two times a year. Tehuacana and Catfish Creeks, which empty into upper Segment 0804, are the only selected tributaries that have averaged more than two samples per year since 2003. For most of the key parameters, the majority of samples were collected in the months of June, July, September and November (Table 7-2). It must be emphasized, however, that the patterns presented in Table 7-2 are based in large part on Tehuacana and Catfish Creeks in Segment 0804, where sample data were more numerous.

Considering the direct hydrological connections between Bedias, Harmon, Kickapoo, and White Rock Creeks to Lake Livingston, sampling along these tributaries likely should receive more attention. Kickapoo Creek on the east side of Lake Livingston is a large tributary that has good streamflow records from a USGS gage, but so little water quality data that its data were considered too sparse to warrant inclusion in this study. A few years of frequent sampling for key parameters in these tributaries would improve understanding of water quality in these creeks that flow directly into Lake Livingston and some instances flow into coves.

Of note, *E. coli* data for these tributaries is quite limited and loading results for *E. coli* as presented in Chapter 5 for the lower area of the watershed were based on fecal coliform data converted to *E coli* based on an assumed general ratio (see Chapter 5, section titled Development of Loading Estimates). To refine loadings estimates and trends in bacteria going into Lake Livingston from these tributaries, increased monitoring of *E. coli* could be considered

Table 7-2 Distribution of samples by month for each of the 15 key parameters, tributaries of the Trinity River and Lake Livingston, surface samples, 1991 – 2011. Shading is relative to each month within each parameter row; the 8 stations used are identical to those in Table 3-3

Tributaries													
Parameter	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**TOTAL**
NH_3	13	21	23	25	21	29	29	15	28	16	23	22	265
TKN	4	8	13	10	8	7	12	4	16	9	2	13	106
NO_3	3	8	3	5	2	4	9	2	4	3	10	4	57
NO_{23}	9	20	19	20	17	25	25	12	16	10	21	12	206
OP	13	20	23	25	20	29	27	12	27	16	21	22	255
TP	7	13	16	15	13	13	18	8	22	13	14	18	170
Chl-a	1	8	9	9	4	8	13	3	13	5	17	8	98
SO_4	11	21	24	25	21	33	28	15	28	17	22	21	266
E. coli	3	6	8	5	4	6	8	3	7	8	10	7	75
TSS	11	16	22	22	15	26	27	12	25	15	22	21	234
BOD_5	6	9	9	11	10	10	11	6	6	5	2	5	90
Fcoli	2	5	1	3	2	6	4	3	8	3	13	5	55
pH	16	21	25	28	19	33	31	16	28	18	29	24	288
Alky	5	9	11	12	7	16	16	7	20	11	23	16	153
WaterT	16	23	25	28	22	33	31	16	28	18	29	24	293
TOTAL	120	208	231	243	185	278	289	134	276	167	258	222	***2611***

Lake Livingston

Between 1993 and 2005, 17 stations in Lake Livingston were intensively sampled for many of the key parameters providing a robust body of water quality data for that time period (Table 3-4). Since then, the only stations that have been sampled consistently more than five times a year are 10917 and 10914 in the upper two AUs of the lake. Stations that have been lightly, but regularly sampled, since 2005 are 10913 (AU 0803_07), 10911 (AU 0803_06), 10909 (AU 0803_05) and 10899 (AU 0803_01). Thus, Station 10913 is the only sampling location between Onalaska and Riverside that has been sampled with some consistency since 2005. This station is situated immediately above White Rock Cove, thus, largely representing the water quality of Lake Livingston above Onalaska (Figure 3-4).

In 2010, several vertical profile measurements and 24-hour multiprobe deployments were conducted at the 14000-series stations in September – November, though this monitoring only included the basic mulitprobe parameters of WaterT, DO, pH and specific conductance. This monitoring gives the impression of heavy sampling simply according to the number of records at these 14000-series stations, when, in reality, no nutrient, ion or bacteria samples were collected and sampling was limited to fall months (Table 3-4). The majority of records at the 10000-series stations in 2010 were also accounted for with profile sampling events. That said, a few fairly comprehensive surface samples and diel events were included in the 2010 lake sampling regime.

February and August stand out as months of more intensive sampling for most of the key parameters in the select 17 stations of Lake Livingston (Table 7-3). This pattern is driven largely by the intensive sampling that occurred throughout the lake between 1993 and 2005 (Table 3-4). Nitrate loadings to Lake Livingston are of considerable concern, yet NO_3 is the least represented water quality parameter in the lake besides BOD_5. Bacteria monitoring has also been limited relative to other parameters. Nearly 200 of the 333 samples of *E. coli* have been taken at the upper two stations (10917 and 10914). More frequent sampling for bacteria has occurred in the warm season, but since periods of high bacteria in the upper lake are associated with cool season months when inflow from the Trinity River is greatest, more cool season monitoring of bacteria might be considered.

Chl-a and pH have been sampled most intensively in August. This scheme may be appropriate since August is the month of greatest concern regarding those parameters. However, September and October should be considered for increased sampling effort, since pH actually peaks in September at Station 10911 (Figure 3-4) and Chl-a exhibits high readings well into the fall.

A notable point about the Lake Livingston dataset among selected stations is that BOD_5 data are completely absent (Table 7-3). This absence is more of a concern for the uppermost stations (10917 and 10914), which are more riverine and have greater potential to have DO levels impacted directly by organic loadings from the Trinity River. However, BOD5 is not considered one of TCEQ’s routine water quality parameters, so absence of sampling for this parameter should not be considered a significant negative.

Table 7-3 Distribution of samples by month for each of the 15 key parameters, Lake Livingston surface samples, 1991 – 2011. Shading is relative to each month within each parameter row; the 17 stations used are identical to those in Table 3-4

Lake Livingston													
Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
NH_3	75	114	71	68	61	70	70	135	67	58	53	67	909
TKN	55	44	50	58	54	59	60	57	44	50	43	54	628
NO_3	29	23	26	20	18	31	24	44	13	24	20	29	301
NO_{23}	44	90	44	52	28	50	48	103	30	33	25	42	589
OP	75	117	61	62	52	75	66	134	62	58	46	62	870
TP	54	43	52	55	55	60	58	62	57	49	37	52	634
Chl-a	45	38	48	52	53	50	54	57	41	38	28	35	539
SO_4	74	88	67	72	62	73	62	103	71	55	51	65	843
E. coli	30	24	27	34	27	28	30	37	24	29	21	22	333
TSS	72	60	66	74	59	67	72	73	64	60	51	69	787
BOD_5	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Fcoli	32	31	30	38	25	38	34	37	27	24	26	33	375
pH	83	180	77	73	62	78	74	219	89	68	58	68	1129
Alky	68	58	66	70	68	74	68	82	66	63	51	68	802
WaterT	84	182	81	74	64	79	76	222	89	68	57	69	1145
TOTAL	820	1092	766	802	688	832	796	1365	744	677	567	735	***9884***

Recommendations to Monitoring Program

While the understanding of water quality in Lake Livingston, the Trinity River, and immediate tributaries has benefitted from a long history of monitoring, certain areas of weakness became apparent through the Phase I study. Additionally, monitoring and subsequent laboratory analyses are resource intensive and always limited by personnel availability and budget constraints. Finally, most data collections efforts will be providing data that are entered into the TCEQ Surface Water Quality Monitoring Information System wherein the data will most likely be used in the State's biennial assessment of water bodes as required under 305(b) of the Clean Water Act. Temporal and spatial biases in monitoring programs, which are typically unintentional, can result in unintended consequences in the 305(b) assessment process as well as improper characterization of water quality compromising optimal management of resources.

The following recommendations for the existing monitoring program are being made to overcome deficits noted in this Phase I study while attempting to minimize temporal and spatial biases. The following recommendations do not consider personnel and budgetary constraints, which would drive the decision as to which recommendations to implement. Recommendations for the existing monitoring program include:

- Implement broader routine water quality monitoring in both time and space for the larger creeks directly entering Lake Livingston, such as Kickapoo Creek, White Rock Creek, and Bedias Creek in order to better characterize the importance of local inflows to lake water quality and possible implications on coves and the main body to the lake. This monitoring should consider many of the parameters considered in this Phase I analysis, but the typical routine parameters used by TCEQ and in the Clean Rivers Program are sufficient for the vast majority of water quality analysis.
- Increase routine monitoring frequency at key Lake Livingston stations with historical data to better characterize intra-annual water quality. Stations to be considered for monitoring should include those that have been referred to in this study as the 10000-series stations (i.e., Stations 10917, 10914, 10913, 10911, 10909 and 10899) and perhaps an additional station or two in the lower main body of the lake, which appears underrepresented in the present monitoring.
- Continue a frequent level of monitoring of several times per year at Station 10934 in upper portion of Segment 0805 and Station 13690 in the lower portion of Segment 0804; both on the Trinity River between Lake Livingston and DFW area. Trinity River-located stations such as 10925 and 10922, which have a history of inconsistent monitoring, could be included into this broader monitoring program.
- Within Lake Livingston, implement a seasonally balanced 24-hour DO monitoring program better reflecting TCEQ assessment guidance that indicates at least one half of the 24-hour DO monitoring events must be spaced over an index period representing warm-weather seasons of the year (March 15-October 15), but also considers that although samples over the entire year are not required at this time, current monitoring guidance encourages year-round sampling. Currently a preponderance of 24-hour measurements is concentrated in the months of July – October. Because 24-hour monitoring through multiprobe deployment includes the basic four field parameters of DO, WaterT, pH, and specific conductance, this suggestion will also provide additional data to characterize pH maximums in the lake.

Appendix B contains FY2013 monitoring schedule for Segments 803, 804 and 805 based on information from the coordinated monitoring website (https://cms.lcra.org/) for reference.

Recommendations for Phase II Study

The findings of the Phase I study provide the basis for Phase II of the project in fiscal year 2013. Recommendations for Phase II include:

- Task 1: Focused review of loading estimates for all water quality parameters developed in Phase I with special attention placed on NO_3 and NO_{23} along the Trinity River and within the upper portion of Lake Livingston to the City of Huntsville water intake at river mile 186.

- Task 2: Initial development of the modeling system focusing on a CE-QUAL-W2 model of Lake Livingston using as a basis the existing Lake Livingston segmentation developed to perform various evaluations of the proposed hydroelectric project on the lake.

- Expand the existing segmentation of Lake Livingston by extending the present segmentation from its upstream terminus at approximately river mile 172 to at least the end of the lake at river mile 222.
- Provide the needed inflows and water quality loadings to the model using the loading algorithms developed in Phase I and as enhanced in the first task of Phase II.
- Provide an initial calibration of the model against measured in-lake data for a selected two-year period within 1993 – 2004; a period of time when extensive monitoring was occurring in Lake Livingston.
- Operate the model to assess NO_{23} in Lake Livingston focusing on the area of the City of Huntsville water intake. Determine which set of conditions (such as streamflow and seasonality) are most likely to result in heightened concerns of elevated NO_{23} in the upper lake. (Note: As with many water quality models, CE-QUAL-W2 does not separately simulate nitrite and nitrate, but considers them as the lumped parameter of NO_{23}.)

- Task 3: Provide a written report summarizing the evaluation of loadings, extension of the CE-QUAL-W2 model of Lake Livingston, initial calibration of the model, and the results of scenarios accessing NO_{23} in the lake.

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Appendix A
Tables of Spatial and Temporal Trends in Lake Livingston for 14 Water Quality Parameters

The following tables display both spatial and monthly patterns of 14 select parameters covering surface samples from 1991 – 2010. The values in each cell represent the 75th percentile and deeper shades of color represent higher values. Empty cells had no data. Asterisks indicate n < 3 and values were not color-evaluated. Trends of discharge in the Trinity River near Crockett (USGS 08065350), Bedias Creek (USGS 08065800), and dam releases are presented for ecological context.

Appendix A-1 Nitrogen (mg/L) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Ammonia (mg/L) 75th Percentile	10917	Upper Lake	0.07	0.05	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.07
	10914		0.07	0.07	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06
	10913		0.05	0.06*	0.05	0.05	0.05	0.10	0.03	0.05	0.05	0.06		0.05
	14013		0.02*	0.06	0.02*					0.03	0.01*			
	14010	Mid Lake												
	10911		0.07	0.06*	0.05	0.17	0.05	0.23	0.03	0.05	0.05	0.07*		0.06
	14008		0.02*	0.04	0.02*					0.02	0.01*			
	14007													
	14006	Lower Lake												
	14005													
	10899		0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.10
	14003	Dam	0.02*	0.06	0.02*					0.02	0.01*			
	10909	Kickapoo Cove	0.04	0.05*	0.05	0.05	0.05*	0.05	0.03	0.05	0.05*	0.01*		0.05
	14009		0.02*	0.04	0.02*					0.03	0.01*			
	14014	White Rock Cove	0.07*	0.09	0.02*					0.04	0.01*			

Appendix A-2 Total Kjeldahl nitrogen (mg/L) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Total Kjeldahl Nitrogen (mg/L) 75th Percentile	10917	Upper Lake	1.10	1.30	1.20	0.90	1.10	1.10	0.90	1.00	0.90	1.20	0.95	1.20
	10914		1.20	1.00	1.00	1.00	1.10	1.00	1.05	0.90	1.05	1.05	0.80	1.20
	10913		1.30	1.40*	1.05	0.90	1.30	1.10	1.40	1.50	1.20	1.40		1.25
	14013													
	14010	Mid Lake												
	10911		0.95	1.30*	0.85	1.10	0.85	0.95	1.30	1.10	1.25	1.10		1.10
	14008													
	14007													
	14006	Lower Lake												
	14005													
	10899		0.80	0.70	0.70	0.80	1.00	0.70	0.80	0.80	0.80	0.80	0.70	0.60
	14003	Dam												
	10909	Kickapoo Cove	1.05	1.00*	1.05	1.20	0.80*	1.00	1.00	1.10	0.70*	0.70*		1.50
	14009													
	14014	White Rock Cove												

Appendix A-3 Nitrate nitrogen (mg/L) 75^{th} percentile concentrations by month, Lake Livingston, 1991 – 2010. 75^{th} percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Nitrate (mg/L) 75th Percentile	10917	Upper Lake	4.49	5.24	2.46	3.03	3.20	1.18	5.90	5.10	5.46	6.82	6.78	4.49
	10914		6.10	4.97	2.15	2.42	3.59	1.85	3.19	5.36	3.73	6.00	5.01	4.31
	10913		5.00*	0.73*	1.41*	2.58*	0.67*	0.97	1.57	0.80	1.23*	0.69*		3.70
	14013		1.48*	0.92*	1.50*					1.24				
	14010	Mid Lake												
	10911		1.79*	0.37*	0.89*	1.00*	0.57*	0.86	0.44	0.03	0.28*	0.93*		0.79
	14008			0.61*						0.10*				
	14007													
	14006	Lower Lake												
	14005													
	10899		0.84	1.50	0.75	0.95	0.50*	0.38	0.03	0.03	0.03	0.10	0.22	0.57
	14003	Dam		2.88*										
	10909	Kickapoo Cove	0.38*	0.27*	0.06*	0.09*	0.03*	0.17	0.02	0.03	0.03*	0.01*		0.24
	14009		0.99*	0.84*										
	14014	White Rock Cove	0.65*	0.29*	0.89*					1.44				

Appendix A-4 Nitrite + nitrate nitrogen (mg/L) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Nitrite + Nitrate (mg/L) 75th Percentile	10917	Upper Lake	2.40	5.30	2.71	3.03	3.61	2.50	4.98	5.52	5.48	6.87	5.90	4.25
	10914		6.29	2.73	1.50	2.41	2.64	1.94	1.64	4.64	5.17	6.71	4.11	3.97
	10913		4.34	0.75*	1.43	2.32	0.68*	0.70	1.65	0.92	1.26*	3.43		3.71
	14013		1.49*	1.47	1.51*					1.20	0.64*			
	14010	Mid Lake												
	10911		1.44	0.41*	0.92	1.00	0.60*	0.77	0.24	0.05	0.31*	1.01		0.80
	14008		1.03*	0.98	1.02*					0.03	0.03*			
	14007													
	14006	Lower Lake												
	14005													
	10899		0.96	0.92	0.74	0.73	0.44	0.11	0.03	0.03	0.03	0.12	0.70	0.58
	14003	Dam	1.03*	0.89	1.00*					0.03	0.03*			
	10909	Kickapoo Cove	0.41	0.30*	0.09	0.13	0.05*	0.05	0.03	0.04	0.05*	0.03*		0.25
	14009		0.99*	0.98	1.01*					0.03	0.03*			
	14014	White Rock Cove	0.67*	0.48	0.90*					1.09	0.03*			

Appendix A-5 Orthophosphate phosphorus (mg/L) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Orthophosphate phosphorus (mg/L) 75th Percentile	10917	Upper Lake	0.65	0.47	0.27	0.30	0.29	0.49	0.60	0.92	0.74	0.94	0.70	0.42
	10914		0.56	0.26	0.27	0.20	0.26	0.30	0.23	0.41	0.50	0.60	0.60	0.47
	10913		0.33	0.15*	0.20	0.16	0.10*	0.14	0.20	0.17	0.20	0.32		0.45
	14013		0.14*	0.13	0.11*					0.19	0.11*			
	14010	Mid Lake												
	10911		0.10	0.22*	0.10	0.12	0.06*	0.09	0.11	0.20	0.10	0.20		0.14
	14008		0.10*	0.09	0.08*					0.10	0.07*			
	14007													
	14006	Lower Lake												
	14005													
	10899		0.10	0.11	0.10	0.09	0.06	0.05	0.05	0.08	0.07	0.08	0.10	0.09
	14003	Dam	0.11*	0.09	0.09*					0.09	0.07*			
	10909	Kickapoo Cove	0.05	0.08*	0.05*	0.05	0.02*	0.06	0.10	0.06	0.05	0.02*		0.05
	14009		0.10*	0.09	0.08*					0.12	0.07*			
	14014	White Rock Cove	0.07*	0.06	0.05*					0.15	0.06*			

Appendix A-6 Total phosphorus (mg/L) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Total Phosphorus (mg/L) 75th Percentile	10917	Upper Lake	0.95	0.80	0.59	0.57	0.60	0.77	0.71	0.89	0.87	1.10	0.97	0.90
	10914		0.55	0.51	0.53	0.36	0.40	0.60	0.39	0.80	0.52	0.75	0.80	0.66
	10913		0.53	0.41*	0.40	0.65	0.30	0.26	0.32	0.29	0.40	0.36		0.53
	14013													
	14010	Mid Lake												
	10911		0.33	0.36*	0.20	0.24	0.18	0.21	0.20	0.50	0.30	0.20*		0.24
	14008													
	14007													
	14006	Lower Lake												
	14005													
	10899		0.20	0.20	0.20	0.16	0.20	0.14	0.12	0.17	0.20	0.14	0.20	0.20
	14003	Dam												
	10909	Kickapoo Cove	0.24	0.18*	0.50	0.18	0.18	0.19	0.60	0.24	0.18*	0.22*		0.17
	14009													
	14014	White Rock Cove												

Appendix A-7 Chlorophyll-a (µg/L) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Chlorophyll-a (µg/L) 75th Percentile	10917	Upper Lake	35.0	15.0	12.0	6.0	15.0	10.0	16.0	18.0	10.0	15.0	21.0	13.0
	10914		19.0	19.0	17.0	13.0	16.0	25.4	44.0	43.0	28.9	24.0	10.0	11.0
	10913		40.0	2.5*	25.5	21.0	59.0	39.0	43.0	85.0	64.0	63.0		20.0*
	14013													
	14010	Mid Lake												
	10911		32.0	42.0*	29.5	17.0	60.0	42.0	43.0	62.0	81.5	67.3		54.0
	14008													
	14007													
	14006	Lower Lake												
	14005													
	10899		15.0	16.0	17.0	23.0	31.0	19.0	23.0	32.4	32.0	27.5	19.0	11.0
	14003	Dam												
	10909	Kickapoo Cove	30.5	13.0*	69.5	30.0	64.0	46.0	23.0	56.0	58.0*	27.6*		44.0*
	14009													
	14014	White Rock Cove												

Appendix A-8 Sulfate (mg/L) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Sulfate (mg/L) 75th Percentile	10917	Upper Lake	76.0	67.0	74.0	66.0	55.0	64.0	81.5	82.0	72.0	76.0	75.5	59.0
	10914		76.0	72.0	61.0	60.0	71.0	58.5	78.0	78.8	73.0	77.0	70.0	54.0
	10913		66.0	46.0*	45.0	57.0	60.0	66.0	51.0	80.0	50.0	95.0		69.0
	14013		50.0*	41.0	56.0*					57.1	55.8*			
	14010	Mid Lake												
	10911		54.0	46.0*	44.0	57.0	64.0	50.0	51.0	49.0	50.0	58.0*		47.0
	14008									39.0*	34.0*			
	14007													
	14006	Lower Lake												
	14005													
	10899		45.0	47.5	42.0	43.0	47.5	43.0	41.0	44.0	42.5	47.5	47.0	47.0
	14003	Dam	29.6*	40.3	33.6*					39.2	33.8*			
	10909	Kickapoo Cove	45.0	18.0*	38.0	46.0	61.0*	45.0	37.0	39.0	40.0	32.0*		40.0
	14009													
	14014	White Rock Cove												

Appendix A-9 *E. coli* (colonies/100mL) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
***E. coli* (Colonies/100mL) 75th Percentile**	10917	Upper Lake	1954	1400	220	341	115	79	28	260	104	343	160	360
	10914		300	120	230	220	17	98	13	26	15	170	38	86
	10913		20	705*	130*	542	21*	12	2	5	4*	472		58*
	14013													
	14010	Mid Lake												
	10911		4*	431*	26*	9	9*	44*	133	2	9*	4838*		10*
	14008													
	14007													
	14006	Lower Lake												
	14005													
	10899		8	22	2	2	1	2	1	4	43	133	32	2*
	14003	Dam												
	10909	Kickapoo Cove	99*	333*	1*	106	8*	13*	43	4	310*	1*		22*
	14009													
	14014	White Rock Cove												

Appendix A-10 Total suspended solids (mg/L) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Total Suspended Solids (mg/L) 75th Percentile	10917	Upper Lake	190.5	202.0	306.0	232.0	301.0	250.0	117.0	79.0	238.0	247.0	170.0	315.0
	10914		154.5	134.0	232.0	151.0	90.0	85.0	46.0	28.0	47.0	140.0	63.0	197.0
	10913		36.0	115.0	147.0	127.0	98.0	53.0	78.0	36.5	40.0	58.0		59.0
	14013													
	14010	Mid Lake												
	10911		26.0	96.0	62.0	56.0	28.0	18.0	15.2	22.0	22.0	20.0		32.0
	14008													
	14007													
	14006	Lower Lake												
	14005													
	10899		26.0	24.0	22.0	20.0	12.0	7.5	7.0	8.0	10.0	10.5	16.0	13.0
	14003	Dam												
	10909	Kickapoo Cove	26.0	32.0*	35.5	25.0	22.0	16.0	18.0	22.0	25.0	16.0*		37.0
	14009													
	14014	White Rock Cove												

Appendix A-11 Fecal coliform (colonies/100mL) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Fecal Coliform (Colonies/100mL) 75th Percentile	10917	Upper Lake	530	1205	373	350	200	200	150	50	170	600	530	2400
	10914		255	390	250	125	100	50	45	150	30	150	400	2550
	10913		30	1680*	20*	63	9*	90	100	10	60*	44*		100
	14013													
	14010	Mid Lake												
	10911		10*	80*	10*	10	9*	20	10	10	20*	6*		100
	14008													
	14007													
	14006	Lower Lake												
	14005													
	10899		10	20	20	10	10	16	20	20	20	10	20	10
	14003	Dam												
	10909	Kickapoo Cove	2032		30*	25		50	10*	50	40*			150
	14009													
	14014	White Rock Cove												

Appendix A-12 pH 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
pH 75th Percentile	10917	Upper Lake	8.3	8.1	8.0	8.0	8.0	8.1	8.4	8.3	8.1	8.2	8.0	8.0
	10914		8.0	7.9	8.1	8.0	8.4	8.8	8.8	8.9	8.5	8.2	7.9	8.1
	10913		8.3	7.6	7.7	8.3	8.7	8.6	9.0	9.1	8.5	8.7		8.1
	14013		8.1*	8.3	8.2*					9.2	9.5*			
	14010	Mid Lake	8.0*	8.0	8.2*					9.1	9.5*			
	10911		8.2	7.9	8.1	8.3	8.9	9.2	9.1	9.0	9.4	8.5		8.6
	14008		7.9*	8.1	8.2*					8.9	8.8*			
	14007		7.9*	8.1	8.1*					8.9	8.9*	8.5*	8.4*	
	14006	Lower Lake	7.9*	8.1	8.1*					8.8	9.0*	8.3*	8.3*	
	14005		7.9*	8.1	8.0*					8.8	8.9*	8.6*	8.2*	
	10899		8.3	8.0	8.2	8.6	9.0	9.0	9.0	9.0	8.7	8.5	8.1	8.1
	14003	Dam	7.9*	8.0	8.1*					8.9	8.8*			
	10909	Kickapoo Cove	8.6	8.4*	8.7	8.0	9.2	9.0	9.1	8.9	8.6	8.7*		8.4
	14009		7.8*	8.3	8.1*					9.0	8.7*			
	14014	White Rock Cove	7.7*	8.1	8.3*					9.0	9.6*	8.1*	8.5*	

Appendix A-13 Alkalinity (mg/L as $CaCO_3$) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Alkalinity (mg/L as $CaCO_3$) 75th Percentile	10917	Upper Lake	116	120	112	121	131	127	130	132	120	113	112	110
	10914	Upper Lake	105	108	112	115	123	119	118	128	120	111	112	100
	10913	Upper Lake	117	88*	103	119	108	108	112	126	112	106		105
	14013	Upper Lake								112*				
	14010	Mid Lake												
	10911	Mid Lake	109	105*	104	111	115	100	116	110	102	114		104
	14008	Mid Lake												
	14007	Mid Lake												
	14006	Lower Lake												
	14005	Lower Lake												
	10899	Lower Lake	99	98	102	98	100	102	98	106	105	99	106	102
	14003	Dam								82*				
	10909	Kickapoo Cove	103	36*	77	88	98	83	100	99	110	102*		84
	14009	Kickapoo Cove												
	14014	White Rock Cove												

Appendix A-14 Water temperature (°C) 75th percentile concentrations by month, Lake Livingston, 1991 – 2010. 75th percentile flow and dam releases are provided for hydrological context. Darker shades indicate higher concentration; empty cells had no data; asterisks indicate n < 3 and values were not color-evaluated.

	Station	Location	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Flow (cfs)	08065350	Trinity nr Crockett	14000	17300	23400	17200	13800	12700	3425	2160	2700	3080	8140	10850
	08065800	Bedias Creek	240	278	131	50	71	54	12	3	4	8	33	146
Dam Release (cfs)	Dam	Dam	21461	21000	27300	22000	16896	14960	3450	2420	2420	3000	12000	16000
Water Temperature (°C) 75th Percentile	10917	Upper Lake	12.4	15.0	19.9	23.2	27.0	30.1	31.5	32.0	27.0	22.0	16.5	12.6
	10914		13.7	15.3	20.1	23.0	30.0	31.6	33.0	33.2	29.9	23.7	18.3	12.5
	10913		14.0	24.0	20.3	25.1	28.2	31.3	32.4	33.9	28.1	25.4		12.9
	14013		10.0*	14.5	14.0*					32.0	32.5*			
	14010	Mid Lake	11.0*	14.5	13.0*					32.0	32.0*			
	10911		13.8	15.0	21.0	23.9	28.0	32.6	31.6	32.6	28.4	25.8		13.5
	14008		11.0*	14.5	12.5*					30.7	30.0*			
	14007		11.0*	14.0	12.5*					30.9	30.8*	23.2*	16.5*	
	14006	Lower Lake	12.0*	13.5	12.0*					31.0	30.1*	23.4*	18.0*	
	14005		12.0*	14.0	12.0*					30.8	30.0*	24.3*	17.6*	
	10899		12.8	14.3	18.0	23.1	26.9	30.8	31.8	31.9	28.8	24.1	19.2	14.1
	14003	Dam	11.5*	14.0	12.0*					31.3	30.5*			
	10909	Kickapoo Cove	16.2	11.7*	20.5	25.2	31.0	34.0	34.1	32.7	31.0	28.2*		14.8
	14009		10.0*	14.5	12.5*					30.9	30.0*			
	14014	White Rock Cove	9.5*	15.5	14.5*					33.0	32.5*	23.6*	16.1*	

Appendix B

FY2013 Coordinated Monitoring Schedule for Segments 803, 804 and 805

Table B-1 FY2013 Coordinated Monitoring Schedule for Segment 803. SE, submitting entity; CE, collecting entity; and MT, monitoring type. TR=TRA, WC=TCEQ, LL=TRA Lake Livingston Project, FO=TCEQ Regional Office, BS=Biased season, and RT=routine.

Site Description	Station ID	Seg-ment	Region	SE	CE	MT	24 hr DO	Metal Water	Metal Sediment	Convent-ional	Bacteria	Field
LAKE LIVINGSTON IN MAIN POOL NEAR DAM AT TRA BOUY #2 4.25 KM WEST OF INTERSECTION OF FM 1988 AND FM 3128	10899	803	10	TR	LL	BS	2					
LAKE LIVINGSTON IN MAIN POOL NEAR DAM AT TRA BOUY #2 4.25 KM WEST OF INTERSECTION OF FM 1988 AND FM 3128	10899	803	10	TR	LL	RT		2		4	4	4
LAKE LIVINGSTON IN KICKAPOO CREEK BAY CHANNEL 66 METERS WEST OF INTERSECTION OF NOEL POINT AND PINEGROVE DRIVE TRA #12	10909	803	10	TR	LL	RT		2		4	4	4
LAKE LIVINGSTON 4.39 KM EAST AND 1.17 KM SOUTH OF INTERSECTION OF US 190 AND FM 980 WEST OF ONALASKA	10911	803	10	TR	LL	RT		2		4	4	4
LK LIVINGSTON 1.8 KM S AND 496 METERS E OF INTERSECTION OF FM 356 AND DAVIS RDIN MAIN CHANNEL NEAR MOUTH OF WHITE ROCK CREEK BAY TRA 6	10913	803	10	TR	LL	RT		2		4	4	4
LAKE LIVINGSTON AT SH 19 SOUTH OF TRINITY USGS SITE JC	10914	803	12	TR	LL	BS	2					
LAKE LIVINGSTON AT SH 19 SOUTH OF TRINITY USGS SITE JC	10914	803	12	TR	LL	RT		4		12	12	12
LAKE LIVINGSTON HEADWATERS AT SH 21 NORTHEAST OF MID WAY TRA 97	10917	803	10	TR	LL	RT		4		12	12	12
LAKE LIVINGSTON USGS SITE BC 550 METERS SOUTH AND 2.32 KM EAST OF INTERSECTION OF WALNUT POINT DRIVE AND CAPE ROYALE	14005	803	10	TR	LL	BS	2					

Site Description	Station ID	Seg-ment	Region	SE	CE	MT	24 hr DO	Metal Water	Metal Sediment	Convent-ional	Bacteria	Field
LAKE LIVINGSTON USGS SITE CC 3.64 KM WEST AND 1.31 KM SOUTH OF INTERSECTION OF FM 3277 AND NORMAGENE STREET	14006	803	10	TR	LL	BS	2					
LAKE LIVINGSTON USGS SITE DL 1.27 KM NORTH AND 2.81 KM WEST OF INTERSECTION OF FM 3277 AND FM 2457	14007	803	10	TR	LL	BS	2					
LAKE LIVINGSTON USGS SITE HC 280 METERS SOUTH AND 363 METERS EAST OF INTERSECTION OF 2ND STREET AND FM 356	14014	803	10	TR	LL	BS	2					
HARMON CREEK 509 METERS UPSTREAM FROM INTERSECTION WITH OTTER RD EAST OF FM 980 AND 7.6 MILES NORTHEAST OF HUNTSVILLE	10698	0803A	12	TR	LL	RT				2	2	2
WHITE ROCK CREEK 2.77 KM DOWNSTREAM OF CONFLUENCE WITH CEDAR CREEK NORTHEAST OF TRINITY TRA #21	10696	0803B	10	TR	LL	RT				2	2	2
NELSON CREEK AT FM 3478 NEAR MOUNT OLIVE TRA #20	10700	0803E	12	TR	LL	RT				2	2	2
BEDIAS CREEK AT BRIDGE ON FM 247 EAST OF MADISONVILLE	10702	0803F	9	TR	LL	RT				2	2	2
MADISONVILLE LAKE MID LAKE 460 M N AND 371 M W OF INTERSECTION OF PARKHILL DR AND COLLARD ST 334 M NORTH OF DAM NE OF MADISONVILLE	16953	0803G	9	WC	FO	RT		4	4	4		4
						Totals	12	20	4	52	48	52

Table B-2 FY2013 Coordinated Monitoring Schedule for Segment 804. SE, submitting entity; CE, collecting entity, MT, monitoring type. TR=TRA, WC=TCEQ, LL=TRA Lake Livingston Project, FO=TCEQ Regional Office, TD=Tarrent Regional Water District, BS=Biased season and RT=routine.

Site Description	Station ID	Seg-ment	Region	SE	CE	MT	Metal Water	Organic Sediment	Convent-ional	Bacteria	Flow	Field
TRINITY RIVER IMMEDIATELY DOWNSTREAM OF US 79 NORTHEAST OF OAKWOOD	10919	804	5	TR	TR	RT	2		4	4	4	4
TRINITY RIVER AT SH 31 IN TRINIDAD	10922	804	4	TR	TR	RT	2		4	4	4	4
TRINITY RIVER 304 METERS UPSTREAM OF SH 7 11.9 MI WEST OF CROCKETT	13690	804	10	TR	LL	RT	4		12	12	12	12
LOWER KEECHI CREEK 110 METERS UPSTREAM OF FM 811 IN LEON COUNTY	20382	804	9	WC	FO	RT	4		4		4	4
TEHUACANA CREEK 20 METERS DOWNSTREAM OF SH 75 SOUTHEAST OF STREETMAN	10705	0804F	9	TR	TD	RT	2		2	2		2
TEHUACANA CREEK IMMEDIATELY UPSTREAM OF FM 488/RR 488 IN FREESTONE COUNTY	20770	0804F	9	WC	FO	RT	4		4	4	4	4
CATFISH CK IMMEDIATELY DNSTM OF UNNAMED RD 1.70 KM DOWNSTREAM OF CONFLUENCE WITH LONG CREEK IN ENGLING WMA AT CAMP SITE 3 2.6 MILES E OF BETHEL	10717	0804G	5	WC	FO	RT			4	4	4	4
UPPER KEECHI CREEK IMMEDIATELY UPSTREAM OF FM 542 IN LEON COUNTY	20771	0804H	9	WC	FO	RT	4		4	4	4	4
FAIRFIELD LAKE IN MAIN POOL 751 METERS SOUTH AND 503 METERS WEST OF NORTH END OF DAM 12.9 KM NORTHEAST OF FAIRFIELD	17951	0804J	9	WC	FO	RT		2	4	4		4
						Totals	22	2	42	38	36	42

Table B-3 FY2013 Coordinated Monitoring Schedule for Segment 805. SE, submitting entity; CE, collecting entity, MT, monitoring type. TR=TRA, DA=City of Dallas and RT=routine.

Site Description	Station ID	Seg-ment	Region	SE	CE	MT	Metal Water	Convent-ional	Bacteria	Flow	Field
TRINITY RIVER 50 METERS DOWNSTREAM OF SH 34 NORTHEAST OF ENNIS	10925	805	4	TR	TR	RT	2	4	4	4	4
TRINITY RIVER AT SOUTH LOOP SH 12 SOUTH OF DALLAS	10934	805	4	TR	TR	RT	2	4	4	4	4
TRINITY RIVER 46 METERS UPSTREAM OF N WESTMORELAND ROAD IN DALLAS	10937	805	4	TR	TR	RT	2	4	4	4	4
UPPER TRINITY RIVER 190 METERS DOWNSTREAM OF SOUTH CENTRAL EXPRESSWAY/SH 310 AND 105 METERS UPSTREAM OF RAILROAD BRIDGE	20444	805	4	TR	DA	RT			4	4	4
UPPER TRINITY RIVER AT SYLVAN AVENUE IN DALLAS	20933	805	4	TR	DA	RT			4	4	4
UPPER TRINITY RIVER AT SANTA FE AVENUE IN DALLAS UNDER DART RAIL BRIDGE	20934	805	4	TR	DA	RT			4	4	4
							6	12	24	24	24